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The primary objective of this project was to develop Gas-Fed Pulsed Plasma Thrusters (GF-PPT) that can be used with water vapor or hydrazine as fuel, with vapor pressures of less than 1 Torr necessary to operate the thruster. This propulsion technology can be used to perform orbit phase changes or plane (inclination) changes for near and intermediate-earth orbit satellites. GF-PPT technology is particularly suited for large Δv, in-plane, orbit phase changes. This technology can therefore complement resistoject technology and allow rapid constellation redeployment to insure prompt satellite coverage of conflicts at any location on the surface of the earth with a constellation of satellites optimized for minimum size and cost. This report discusses GF-PPT thruster performance scaling, as well as hardware and power electronics that were developed in this project.

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HIGH EFFICIENCY PULSED PLASMA THRUSTER FOR SATELLITE ATTITUDE CONTROL AND MANEUVER

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1. INTRODUCTION

There is a need to develop compact and efficient propulsion technology that can be used to perform orbit phase changes or plane (inclination) changes for near- and intermediate-earth orbit satellites. This is especially important for platforms intended for high-resolution imagery missions that must loiter in low earth orbits for extended periods of time. Gas-Fueled Pulsed Plasma Thruster (GF-PPT) technology is particularly suited for large Δv, orbit inclination changes (LEO-to-LEO) or orbit transfer from LEO to higher earth orbits (HEO).[1] Resistojet thrusters are suited for missions requiring lower Δv, in-plane, orbit phase changes. This pulsed plasma thruster technology will therefore complement resistojet technology and allow rapid constellation redeployment to insure prompt satellite coverage of conflicts at any location on the surface of the earth with a constellation of satellites optimized for minimum size and cost. This technology can also be used to provide the high Δv orbit maneuvers necessary to refuel satellite constellations from tugs delivered to LEO.

GF-PPTs have been in existence since the 1960's but fell out of favor when no solution could be found for their low mass utilization efficiency.[2,3] The response time of the propellant delivery system in those early thrusters was on the order of several milliseconds and the single power pulse would accelerate only several hundred microseconds worth of propellant that was in transit through the thruster. Only a very small percentage of the propellant was actually accelerated and the remainder left the thruster at thermal velocities, which resulted in unacceptably low mass utilization efficiency. However, the unique capability for pulse plasma thrusters to provide high

specific impulse at arbitrarily small spacecraft bus power makes them particularly suitable for today's power limited small satellites.[4,5,6]

Science Research Laboratory (SRL) has developed a solution to the propellant utilization problem that is based on an all-solid-state modulator with IGBT commutation that allows high repetition rate (10 kHz pulse recurrent frequency) pulsing of the discharge. By delivering multiple micropulses to the thruster during the entire operating cycle of the gas delivery system, this approach results in mass utilization efficiency close to 100%. These gas-fed pulsed plasma thrusters exhibit several desirable characteristics, which, together with their ability to operate with noble gases and water and hydrazine as fuel, make them uniquely capable of conducting the critical satellite orbit changes discussed above. These attributes include

- Small, precise and repeatable impulse bits
- Simple thruster design that enhances reliability
- Relatively high instantaneous thrust density compared to static, electric propulsion techniques
- No spacecraft contamination issues
- Compatibility with a wide range of propellants
- Much wider latitude with energy-to-impulse ratio and thus better performance throttling with a fixed geometry due to independent control of thrust and mass bit
- Much wider range of achievable specific impulses
- Higher potential scalability to low discharge energies and small size and weight

- Absence of particulates or large molecules in the exhaust which adversely impact efficiency
- Operation at low voltage (100-400 volts)

These GF-PPT attributes offer up a 2-3x reduction in propellant mass requirements, thereby reducing the cost of launching and maneuvering satellites. In addition, the solid-state electronics capability of GF-PPTs can extend the useful life in station keeping satellites 1-3 years, thereby prolonging mission lifetime. This is especially important for missions that must loiter in LEO for extended periods of time.

SRL and the Jet Propulsion Laboratory (JPL) have been collaborating on developing a new class of GF-PPT. In this effort SRL completed a design, and fabricated hardware of an upgrade GF-PPT that can utilize noble gases and water/hydrazine as the propellant, which offers significant logistics advantages as a fuel in station-keeping.

2. CHARACTERISTICS AND PERFORMANCE OF SRL GF-PPTs

This section reviews the operating characteristics of GF-PPTs. Much of the background material presented below has been summarized by Dr. John Ziemer, JPL, who has worked with SRL on GF-PPTs.[7,8,9]

2.1. Description of the GF-PPT Thruster

GF-PPTs are electric discharge devices that utilize a plasma discharge sheet to accelerate mass and develop thrust. Referring to Figure 1, uniform plasma is initiated between electrodes, and JxB forces drive the plasma sheet down the length of the electrodes. This plasma sheet entrains gas propellant as it moves downstream. GF-PPTs

have been tested recently using argon and xenon for propellants in both electrode geometries. In general, parallel-plate thrusters have better performance, although there are some circumstances where a coaxial geometry would be better.

Power conditioning technology developed by SRL has brought the GF-PPT back to being an interesting possibility for propulsion. Previous GF-PPTs tested in the 1960s and 1970s were single shot devices with limited lifetime due to the fast-acting valves that were necessary for 100% propellant utilization. With SRL's technology, pulses are grouped together in bursts to allow a single valve cycle for many pulses. This increases valve lifetime, allows for a larger total impulse, and leads to near 100% propellant utilization. The solid-state power conditioning and modular capacitor bank has enabled low-energy (hence low-mass) GF-PPTs. As shown in Figure 2, current waveforms are nearly critically damped due to the low inductance nature of the driving electronics, which leads to high efficiency.

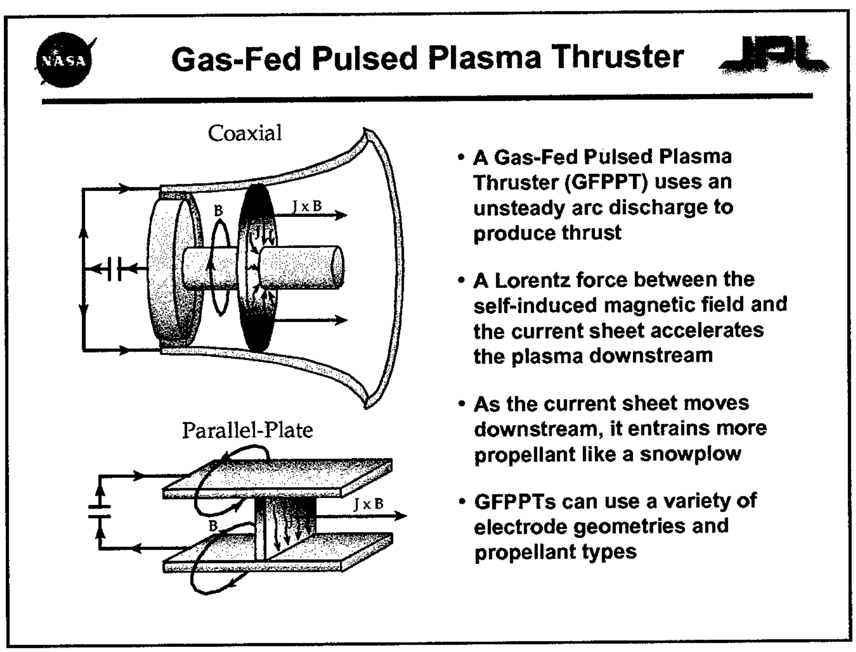

Figure 1. Schematic diagram of a gas-fed pulse plasma thruster.

Advances in GFPPT Design

- Modern GFPPTs have nearly critically damped current waveforms with no reversals
- Due to the burst configuration, instantaneous power is high, but the average power and thrust can still be throttled
- Lower charging voltage allows discharge initiation to be timed more precisely
- Modern thin-film capacitors have lifetimes greater than many billions of pulses

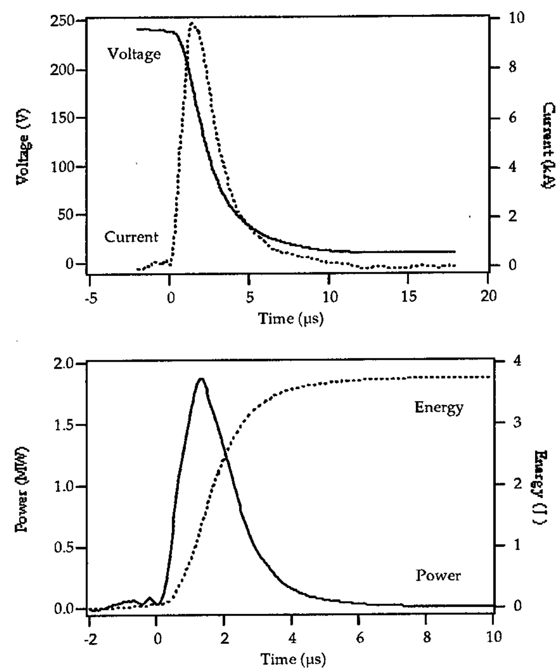

Figure 2. Measured voltage and current discharge waveforms in the JPL/SRL gas-fed pulse power thruster.

SRL has developed a series of GF-PPTs, which were delivered to Princeton University's EPPDyL facility for characterization.[9,10] A summary of these devices is presented in Figure 3. Both coaxial and parallel plate electrode geometries were evaluated, and the PPT-9 has demonstrated ~12% conversion efficiency at a specific impulse of 5000 sec and with a thrust to power ratio of 5 μN/W. This is about 50% of the overall performance goals for GF-PPTs. Figure 4 shows a photograph of the plasma discharge in a coaxial thruster electrode configuration.

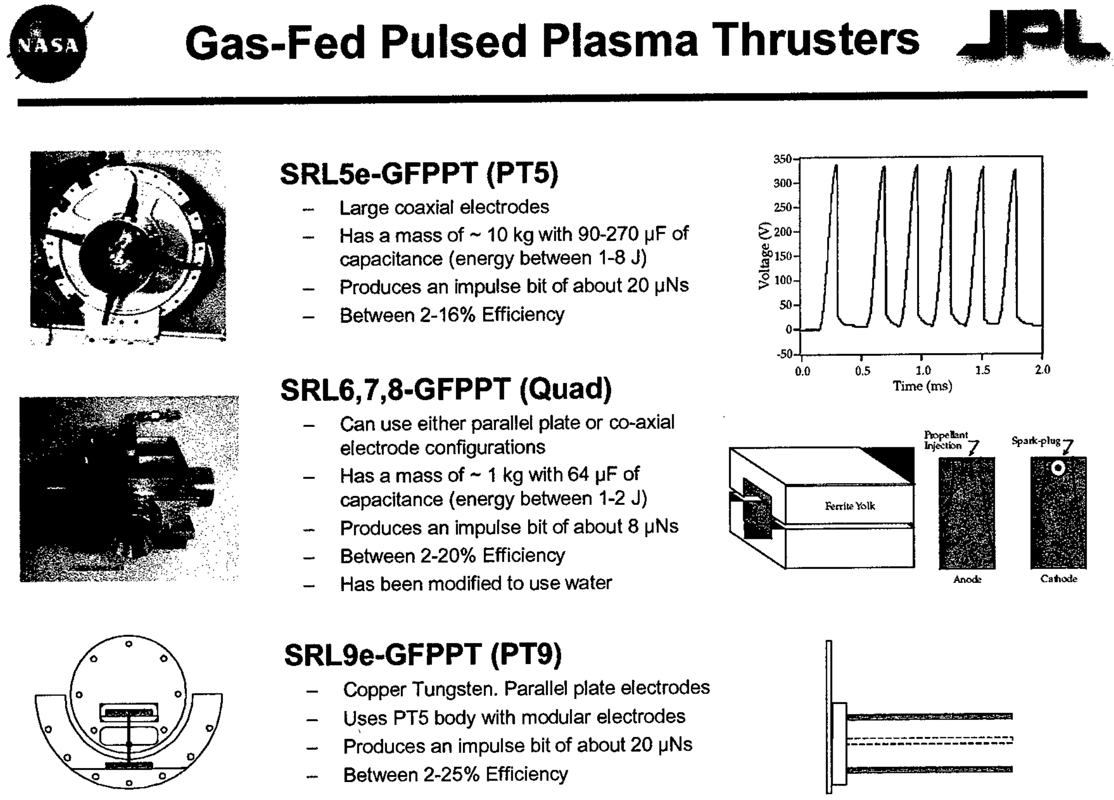

Figure 3. Summary of SRL GF-PPTs tested at Princeton and JPL.

3. GF-PPT PERFORMANCE SCALING

The GF-PPT is powered by an ultra-compact all-solid-state modulator, which combines IGBT commutation with advanced nonlinear magnetic switching technology. Operating lifetime of the thruster system is only limited by discharge electrode erosion and the volume of the propellant supply. Figure 2 showed typical discharge current waveshapes. The critically damped nature of the current waveform is a direct result of the low inductance drive. This allows energy to be coupled efficiently from the electrical power source to the plasma, since the equivalent resistance of the time-varying inductance (dL/dt) caused by the plasma sheath motion dominates the impedance of the pulser and electrical buswork.

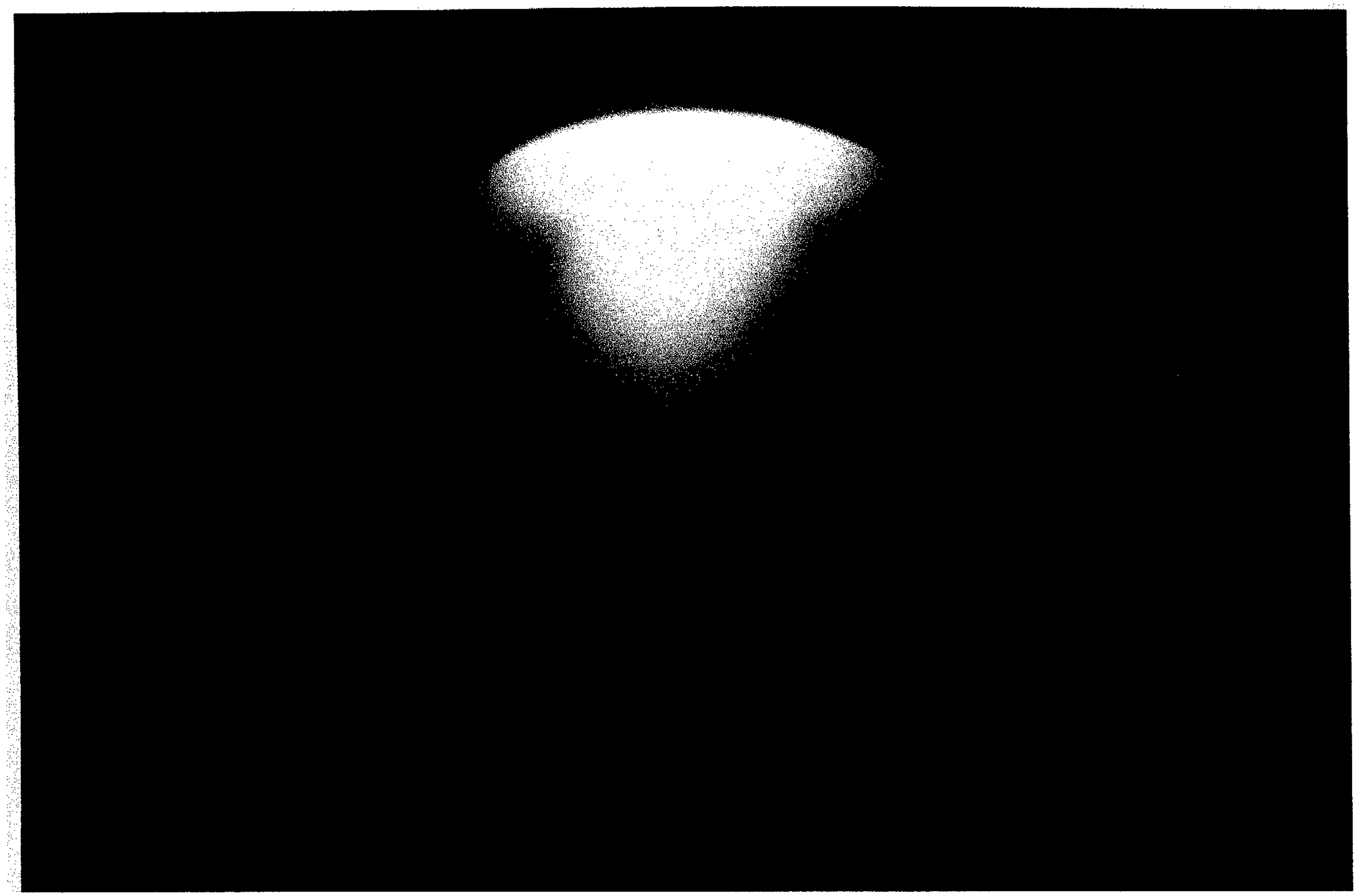

Figure 4. Photograph of the plasma plume in a coaxial GF-PPT.

For a coaxial electrode geometry, after the plasma is initiated, current flow subjects the plasma sheath to a magnetic pressure:

$$P = \frac{B^2}{2\mu_0} = \frac{\mu_0 I^2}{8\pi^2 R^2}(MKS)$$

The $(1/R)^2$ magnetic pressure profile tends to force the plasma sheath to form the shape of a cone. Since acceleration is normal to the surface of the plasma sheath, a sheath geometry that is canted off the electrode surface is wasteful radial acceleration of the propellant. The resulting inefficiency is termed a *Geometric Profile Inefficiency*. In addition the radial dependence of the axial velocity profile results in a *Velocity Profile Inefficiency*. Designing both coaxial and parallel-plate PPT electrodes so as to be as short as practical so as to minimize the final plasma sheath angle best controls these two inefficiencies.

Although the electrode length should be as short as possible, energy is coupled into motion through the time varying inductance (dL/dt) as the plasma sheath moves down the electrodes. The electrical source inductance must be much less than the total change in electrode inductance for efficient transfer of energy from electrical to mechanical. This argues for optimizing both electrode inductance and plasma sheath velocity for maximum dL/dt. The total change in inductance (presently $\simeq$ 10nH) varies linearly with the electrode length (~ 5.0 cm) and attempts to reduce this inductance swing must be matched by equivalent reductions in the source inductance (presently ~ 3-4nH).

In the initial phase of plasma acceleration, the sheath forms on the power input side of the propellant gas column and is driven through the cold gas. The plasma sheath entrains the cold gas as it moves forward in a process sometimes called the *Snowplow*.

During the *Snowplow* phase, the magnetic pressure is balanced by thermal pressure and by the directed kinetic reaction force. The balance of these forces in equilibrium can be written as:

$$\nabla P_{net} = 0 = \nabla\left(\frac{B^2}{2\mu_o} - NkT\right) - \rho\nabla \cdot \mathbf{vv}$$

While the plasma acceleration is in the *Snowplow* phase, energy delivered to the cold gas per unit volume is given as $\mathbf{v} \cdot \mathbf{v}$, but only half of this energy is available as forward-directed kinetic energy (KE=1/2 · ($\mathbf{v} \cdot \mathbf{v}$)), the remainder is deposited thermally and is rapidly converted into radiation. Attempts to convert thermal energy into forward-directed kinetic energy using such devices as nozzles at these elevated temperatures and low densities are negated by radioactive cooling of the plasma. Thus a 50% conversion efficiency is a practical upper limit for a GF-PPT.

Finally, once the plasma sheath has entrained all of the propellant mass, the equilibrium condition is:

$$\nabla \mathrm{P}_{\mathrm{net}} = 0 = \nabla\left(\frac{\mathrm{B}^2}{2\mu_{\mathrm{o}}} - \mathrm{NkT} \right) - \rho \cdot \mathrm{dv/dt}$$

In this case the divergence of thermal pressure is negligible, and the efficiency of converting electrical energy to thrust is only limited by the ratio of (dL/dt)/R (where R is the impedance of the pulser) and profile inefficiencies. For this reason, attempts are made to confine the initial propellant mass to a thin sheet located close to the base of the electrodes.

GF-PPT performance is calculated based on the impulse produced by a measured amount of stored energy and the measured amount of mass that was accelerated. The

efficiency of a GF-PPT is defined here in the conventional manner as a ratio of the directed kinetic energy to the initial stored energy.

$$\eta_t = \frac{(1/2)m_{bit}U_e^2}{(1/2)CV_0^2} = \frac{I_{bit}^2}{m_{bit}CV_0^2}$$

where the mass bit, m_{bit}, is determined from the propellant flow rate and the average exhaust velocity $U_e = I_{bit}/m_{bit}$, C is the capacitance, V_0 is the initial capacitor charge voltage, and I_{bit} is the average impulse of one pulse in a burst. For a GF-PPT, the thrust-to-power ratio is the same as the impulse bit to energy bit ratio,

$$\frac{T}{P} = \frac{I_{bit}}{E} = \frac{I_{bit}}{(1/2)CV_0^2}$$

The specific impulse is the amount of impulse provided by the thruster per unit weight on earth of the propellant used in the pulse,

$$I_{sp} = \frac{I_{bit}}{m_{bit}g} = \frac{U_e}{g}$$

Combining these relations, the GF-PPT thruster efficiency can be expressed as:

$$\eta_t \quad = \quad \frac{1}{2}\frac{T}{P} \cdot I_{sp} \cdot g$$

and thruster efficiency scales linearly with I_{sp}.

3.1 GF-PPT Performance Measurements

Impulse is the key parameter to establish thruster performance, and impulses produced by the GF-PPTs have been carefully measured at two facilities. Both NASA's Jet Propulsion Laboratory and the Princeton University EPPDyL possess large evacuated chambers equipped with swinging gate thrust measurement arms. The thruster is mounted on an arm of known mass. When the thruster is fired a force equal and opposing the

thrust is experienced by the arm of the swinging gate. The resulting acceleration of the arm gives the thrust. The final velocity of the arm determines the impulse.

Figure 5 shows performance data taken on the PPT-9 plasma thruster with argon propellant. The PPT-9 has demonstrated ~12% conversion efficiency at an I_{sp} of 5000 sec and with T/P of 5 μN/W. By comparison, the data indicates the PPT-9 conversion efficiency has dropped to around 4% at a reduced I_{sp} of 2000 sec, which confirms linear efficiency scaling with I_{sp}. These results were achieved with electrode inductance geometry of 5.7 nH/cm and a drive capacitance of 130 μF. The results of the PPT-9 testing in argon showed this particular GF-PPT design is approximately a factor of two lower than the thruster design goals in terms of thruster efficiency and thrust-to-power at the fixed I_{sp} of 5000 sec.

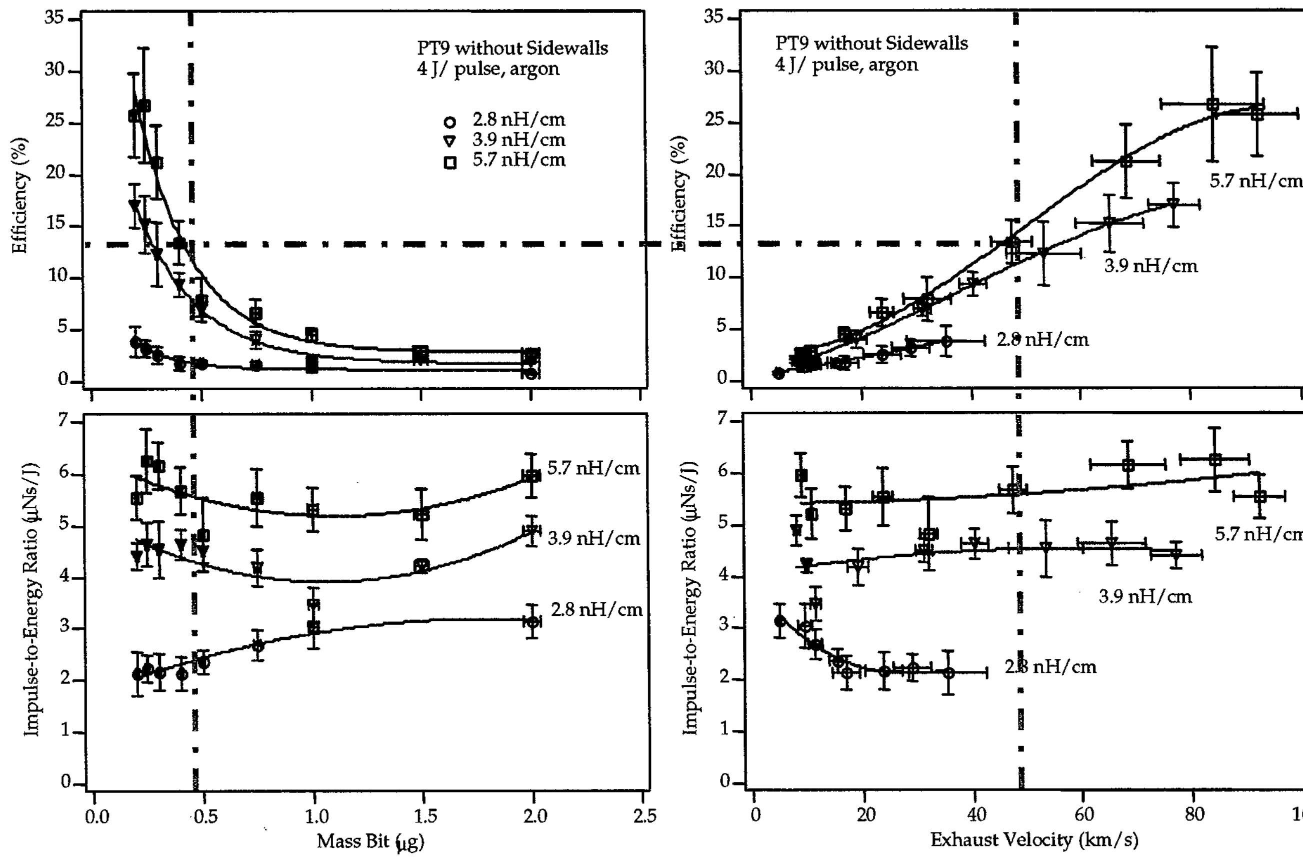

Figure 5. Summary of GF-PPT performance data taken on the PPT-9 thruster with argon propellant.

3.2 Advanced GF-PPT Development

Table 1 predicts how efficiency and impulse scale with circuit parameters, which guided our choice for new design values for advanced thruster hardware. In the upgrade thruster design, we implemented a modified electrode geometry that will increase the distributed electrode inductance from 5.7 nH/cm (PPT-9) to 6.3 nH/cm. This can provide a 10% improvement in thruster efficiency and thrust. We also increased the drive capacitance from 130 μF (PPT-9) to 320 μF, which can deliver more than 50% higher efficiency and thrust. We also reduced the inductance of the driver circuit, which can result in another 15% increase in efficiency and thrust. Rolling up all these performance improvements, our scaling analysis indicates that the advanced thruster can deliver up to 2 times more thrust-to-power and efficiency than realized with the existing PPT-9 thruster.

Table 1. Summary of Projected GF-PPT Thruster Performance Improvements.

Parameter	***PPT-9 Thruster***	***Upgrade Thruster***	***η, I_{bit} Scaling***	***η, I_{bit} Improvement***
Electrode inductance: L’	5.7 nH/cm	6.3 nH/cm	~ L’	1.1
Driver capacitance: C	130 μF	320 μF	$\sim \sqrt{C}$	1.57
Driver inductance: L_o	4.0 nH	3.0 nH	$\sim 1/\sqrt{L_o}$	1.15
Estimated η, I_{bit} Improvement				***2.0x***

Table 2 summarizes projected performance of the advanced thruster design. Improvements in electrode design, increased drive capacitance and lower driver inductance can allow the upgrade GF-PPT thruster to operate up to 12 μN/W at 29% efficiency at an I_{sp} of 5000 sec.

Table 2. Estimated Upgrade Thruster Performance.

Parameter	*PPT-9 Thruster Measurements*	*Design Goal*
Specific Thrust I_{sp}	2000-10,000 sec	< 5000 sec
Propellant	Argon	Argon/Hydrazine
Efficiency	12 % @ I_{sp}=5000 sec	25% @ I_{sp}=5000sec
Thrust-to-Power	5 μN/W @ I_{sp}=5000 sec	>10 μN/W @ I_{sp}=5000 sec
Fuel Utilization	< 90 %	100%

3.3 Advanced GF-PPT Thruster Hardware Approach

The advanced GF-PPT design offers significant improvements over the PPT-9 thruster, and include:

- 2x higher discharge energy
- 8x higher peak and average power ratings
- Much improved plasma ignition design
- Higher repetition rate capability for improved fuel utilization.
- Water-cooled refractor electrodes for extended life

Ignition sparkers are necessary to initiate the plasma discharge down the thruster electrodes, and forming an initial uniform plasma front is critical for entraining propellant and optimizing the thruster energy coupling efficiency. In order to improve plasma ignition, the upgrade thruster will utilize 8 ignition sparkers, compared to 4 for the PPT-9 device. In addition the plasma ignition driver will provide a much higher voltage, faster risetime drive pulse (> 6kV @ 150 nsec risetime) than that currently used on the PPT-9

(~ 2kV @ 400 nsec risetime). Both pulse voltage and risetime across the ignition sparkers are critical for generating sufficiently dense ignition plasma to ensure a uniform plasma sheet during the JxB rundown phase in the thruster discharge.

Table 3. Summary of Upgrade GF-PPT Design Parameters

Parameter	*PPT-9*	*GF-PPT Upgrade*
Discharge energy	4 J	>10 J
Ignition sparkers	4	8
Ignition voltage	2 kV @ 400 ns	6 kV @ 150 ns
Electrodes water cooled	no	yes
Max rep rate (cw)	300 Hz	1000 Hz
Max rep rate (burst)	1000 Hz	10,000 Hz
Average power capability	1500 W	10 kW
Burst power capability	5 kW	100 kW @ 100 ms

Another key improvement in the upgrade thruster is its capability to operate at high repetition rates (up to 10 kHz, compared to 1 kHz for the PPT-9). This will allow the thruster to utilize the propellant mass more effectively, which equates to improved thruster efficiency. Also, the discharge electrodes are constructed from refractory materials and are water-cooled in order to supply extended operating lifetime.

Photographs of prototype configurations for the advanced GF-PPT thruster hardware are shown in Figures 6 and 7. Here a coaxial electrode exhaust configuration is shown. The thruster body measures approximately 18 in diameter by 18 in high, and weighs 30 lbs. It is designed for operating with 320 μF, but can accommodate an additional 100 μF if efficiency measurements indicate that even higher energy storage is

beneficial to thruster operation. This thruster body also includes plasma ignition cabling as well as water-cooling and diagnostics. It should be understood that the size and weight of the thruster body has been designed for easy assembly and test. In actual practice, a space-qualifiable thruster body would be less than 20% of the size and weight shown in Figure 7.

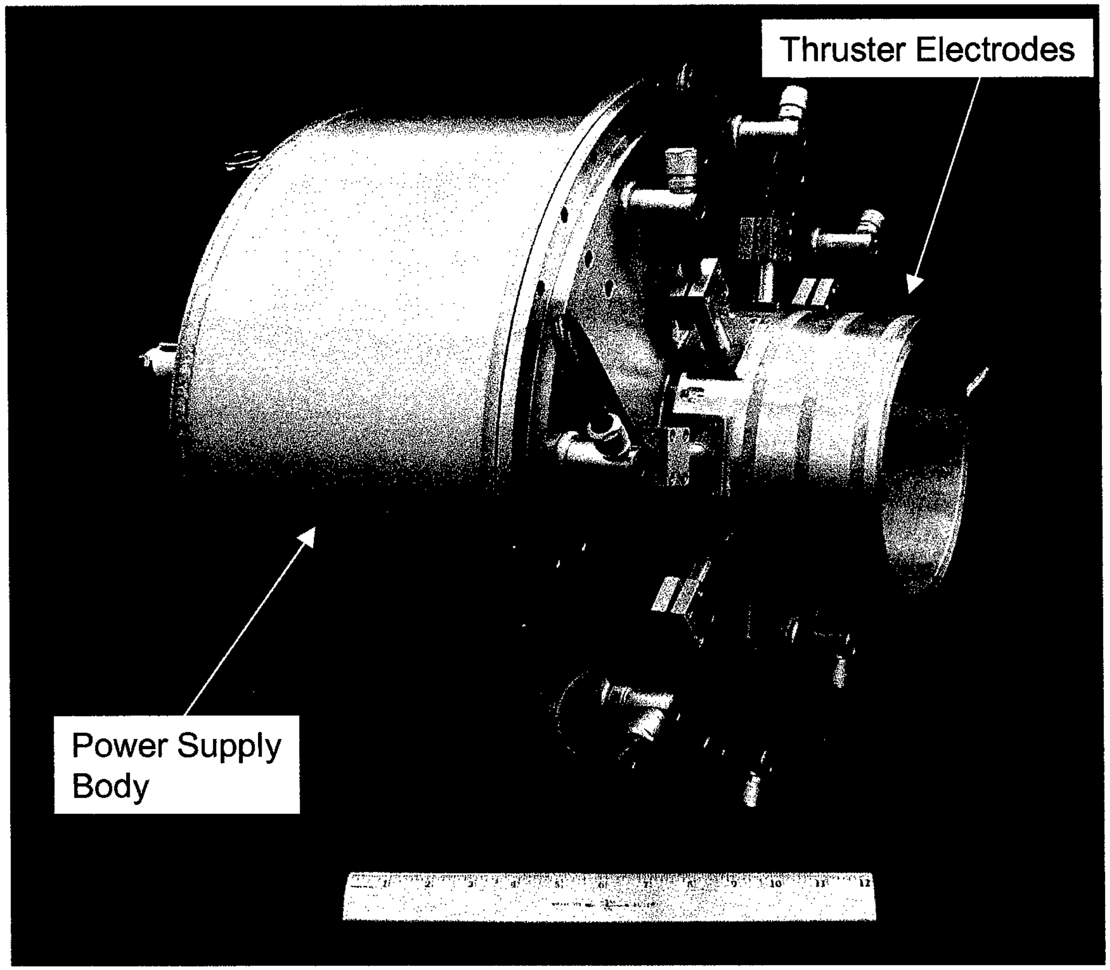

Figure 6. Advanced GF-PPT hardware developed on the DARPA effort.

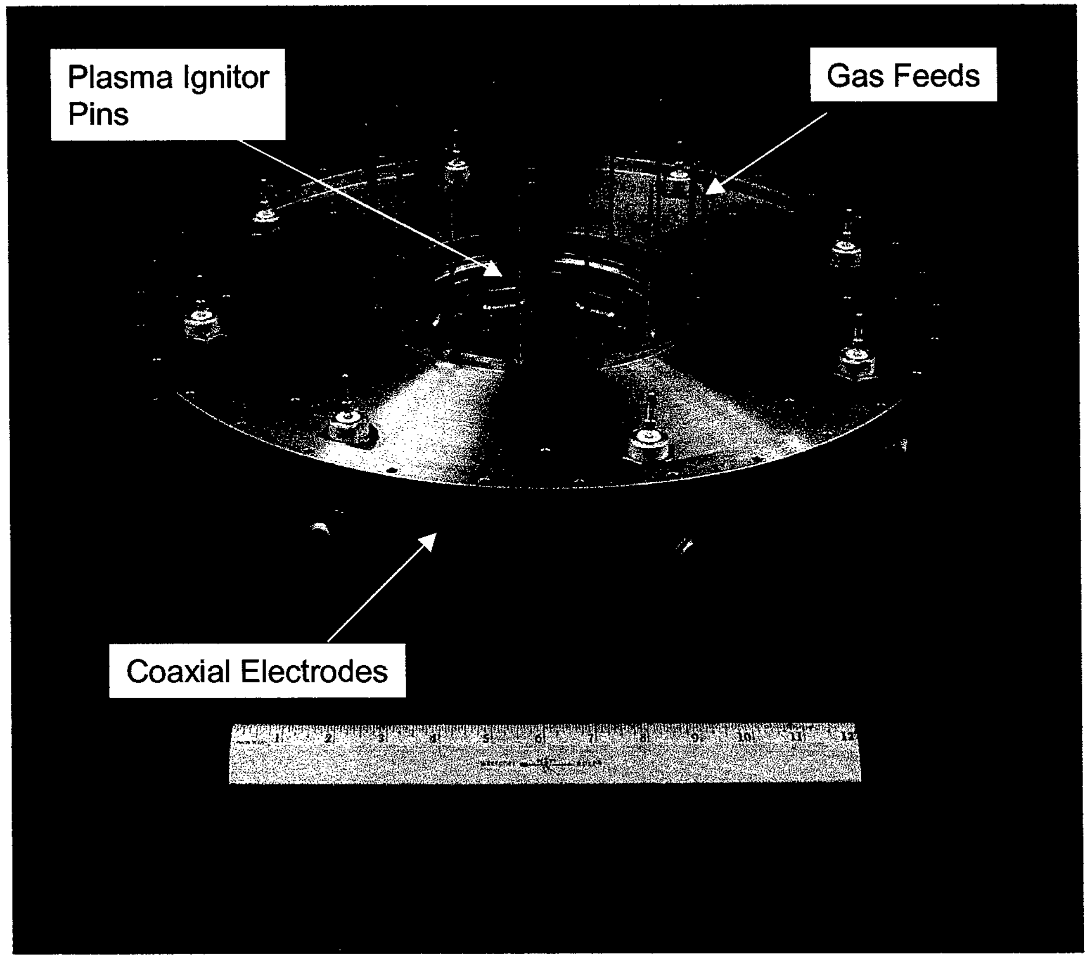

Figure 7. Photograph of the plasma ignitors and gas feed for an advanced GF-PPT.

4. SUMMARY OF ADVANCED GF-PPT DEVELOPMENT AND TESTING

SRL has developed advanced GF-PPT thruster hardware that offers a significant advance in electric thruster technology and performance. We have designed the GF-PPT hardware to produce 25% thruster efficiency using noble gases and/or hydrazine as the fuel. As part of the development program, SRL has designed, fabricated and tested a requisite 10 kW average power modulator for driving the GF-PPT, as well as the new GF-PPT hardware described above.

4.1. 10 kW GF-PPT Modulator Development

A 10 kW power modulator was developed at SRL in order to charge the pulse plasma thruster capacitor at high repetition rate (1 kHz continuous, and 10 kHz in burst mode) and to trigger its energy into the gas discharge load. The modulator is made of two separate units. The first unit is a capacitor charging power supply and the second unit is a pre-ionizing power supply that generates synchronized high voltage ignition pulses for triggering the thruster capacitor energy into the gas discharge load. Photographs of these units are shown in Figures 8 and 9, respectively. The thruster modulator can be operated in two different modes, i.e., cw or burst mode. The modulator operates up to 1 kHz frequency in cw mode, and at a maximum of 10 kHz frequency in burst mode up to 10 ms burst duration. Various electronic safety features have been implemented for safe and reliable operation of the thruster modulator. The electronic protection circuits monitor the currents in various sections of the modulator, and upon detecting a fault situation, the power electronics is quickly disabled. The complete specifications of the thruster modulator are given in Table 4.

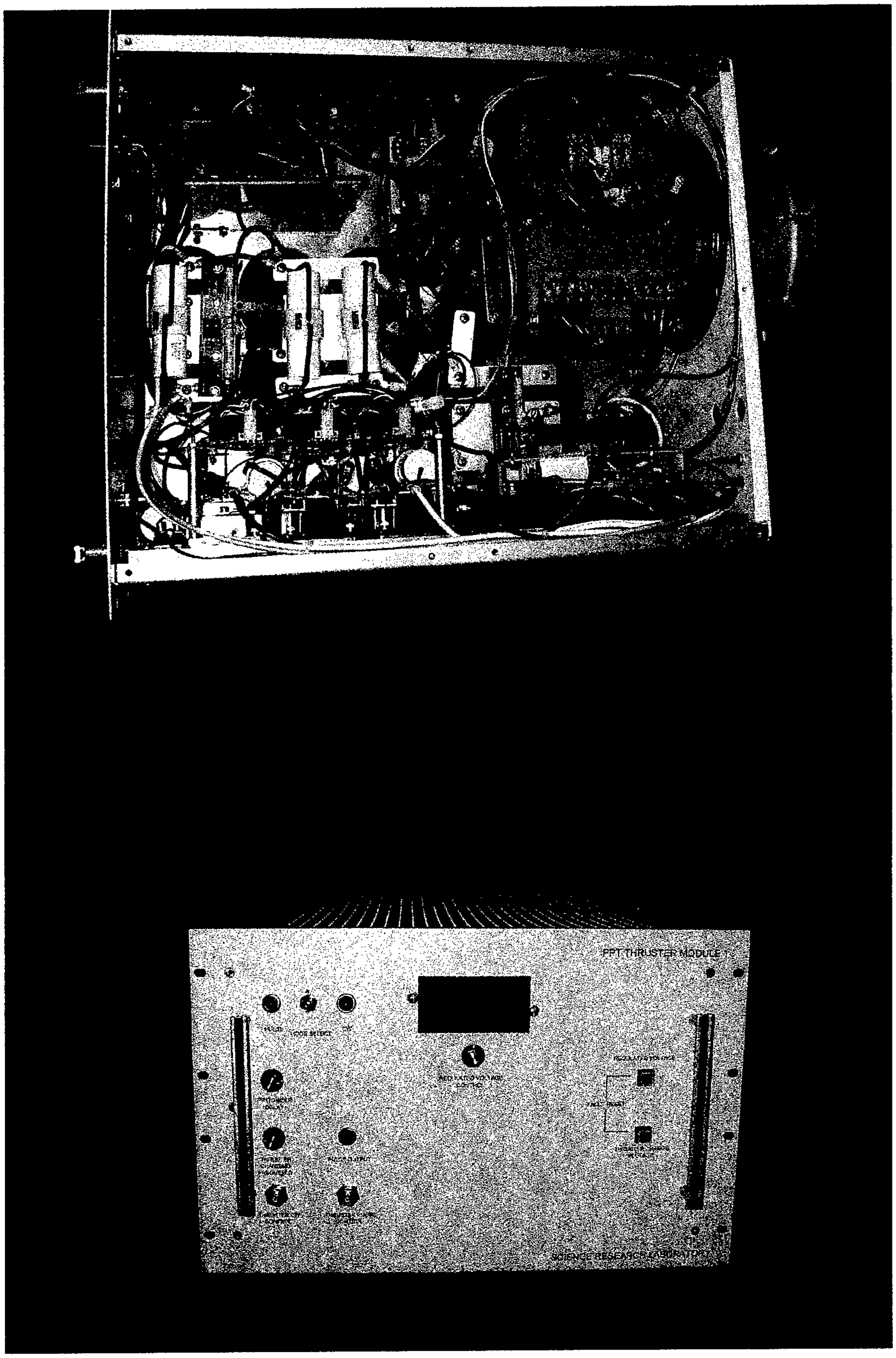

Figure 8. Photograph of the GF-PPT capacitor 10 kW charging module containing buck regulator and bridge inverter.

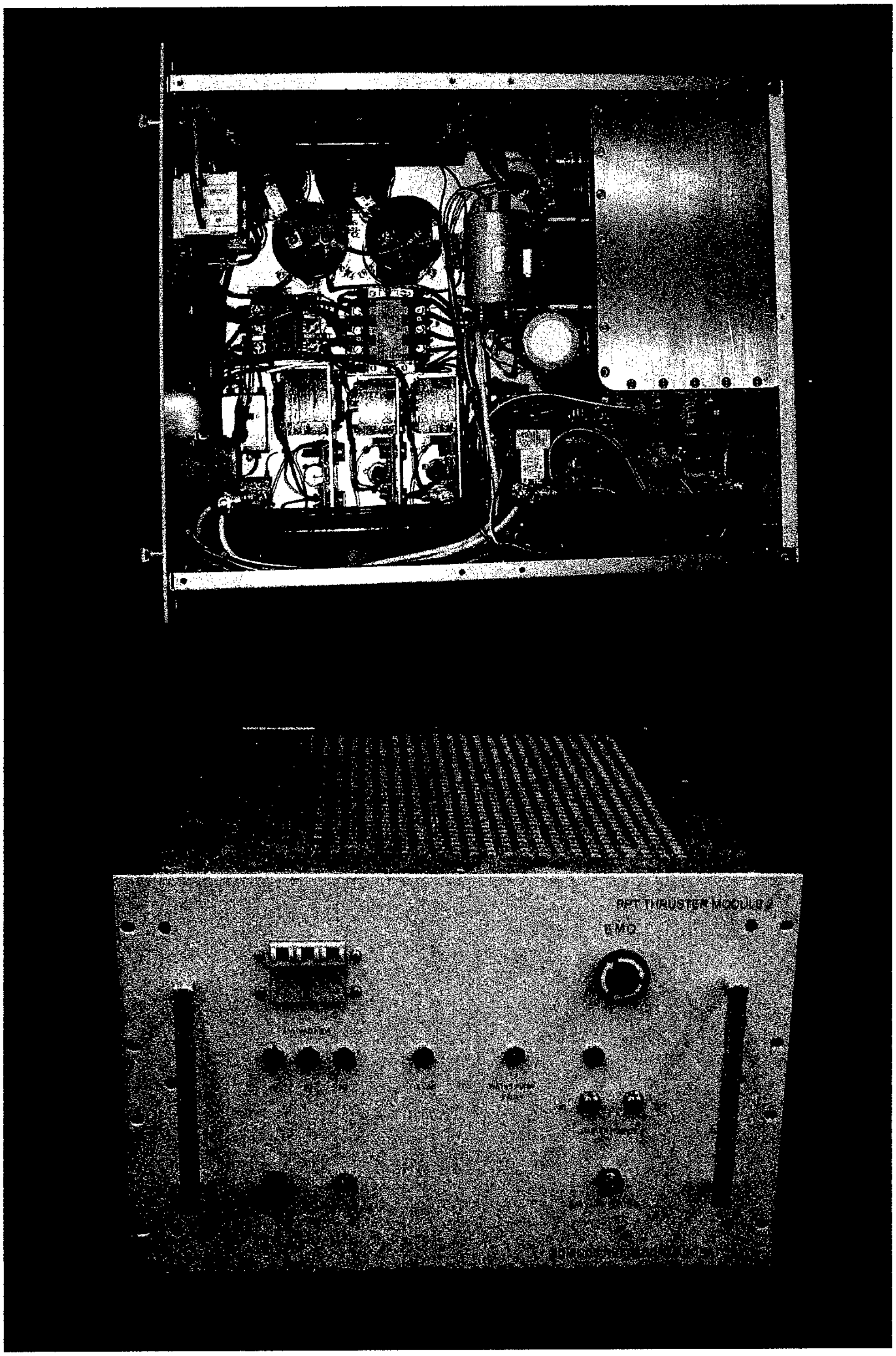

Figure 9. Photograph of the GF-PPT thruster high voltage pre-ionizer module containing unregulated 650Vdc power and preionizer circuit.

Table 4. Summary of GF-PPT Power Electronics Capabilities.

Parameter	*Specifications*
Thruster Capacitor Charging Power Supply	
Capacitance	320 μF
Charge Voltage	variable from 25 V-250 V
Maximum charge energy	10 J / pulse
Operation modes	CW and burst
Charging frequency	300 Hz-1 kHz in CW mode
Burst mode duration	1 – 10 ms
Charging frequency in burst mode	3 kHz – 10 kHz
Capacitor charging time	80 μs / cycle
Pre-ionizer Power Supply	
Output voltage	5kV across 25 nF @ 270 ns risetime
Preionizer frequency	same as charging frequency
Preionizer delay	0-200 μs in CW mode 0–10 μs in burst mode
Safety features	Soft start slope : 50 ms •Peak current limit through buck regulator to 50 A •Buck regulator shut down at 100 A •Inverter shutdown at 400 A •Pulse sequence reversal protection implemented by D-latch •Preionizer designed withstand continuous short circuit and open circuit of the load.

GF-PPT Preionizer Power Supply: A pre-ionizer power supply that generates high voltage pulses is needed to externally trigger the GF-PPT, and allow uniform plasma development and plasma rundown along the thruster electrodes. Uniform plasma development is key to realizing an efficient thruster. Referring to Figure 10, the pre-ionizer power supply houses an unregulated 650Vdc power supply and high voltage pulser circuit. The 650 Vdc power is obtained after rectification and filtering 3-phase 480

VAC 60 Hz wall plug power. A 500 μH inductor and 2400 μF capacitor is used to filter the rectified voltage. A 3-stage magnetic pulse compression (MPC) circuit is used to generate fast-risetime, high voltage pre-ionization pulses. Each compression stage has 25 nF capacitor. Two 1200V, 400A rated IGBT switches are used in parallel to generated a 1.2 kV pulse across the primary winding of a 1:5 step up ratio pulse transformer. Secondary winding of the pulse transformer launches a 6 kV pulse into a 3-stage MPC circuit. After the compression stages a 6 kV pulse appears across the last capacitor C3 of MPC circuit. Figure 11 shows the measured output pulses across 25 nF capacitor. All the ferrite cores of the MPC are reset by a single pass conductor carrying 10 A dc current.

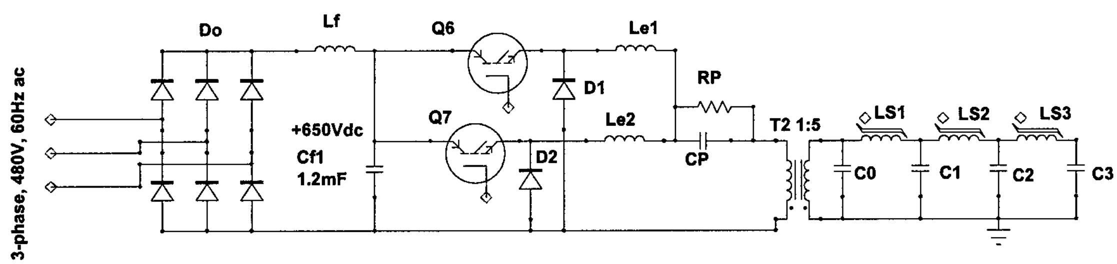

Figure 10. Top-level schematic of the GF-PPT preionizer module.

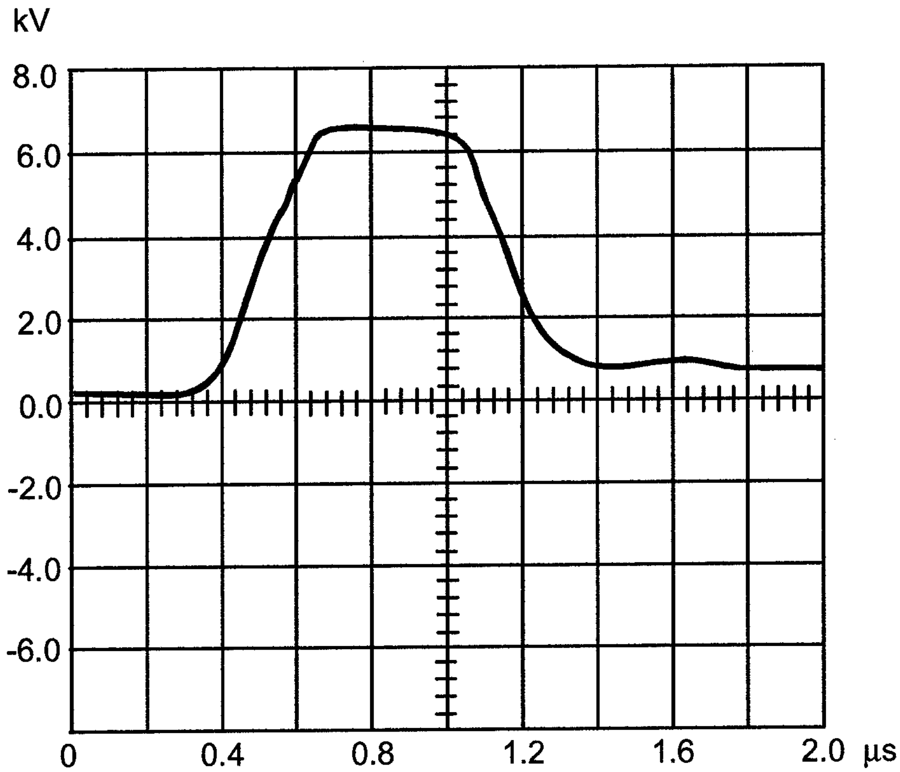

Figure 11. Preionizer high voltage pulse across C3 (25 nF) capacitor. The risetime is less than 270 ns.

Thruster Capacitor charging unit: Photographs of the capacitor charger module were shown earlier in Figures 8 and 9. The capacitor charging circuit is made of two circuits, namely a buck regulator and a bridge inverter. Referring to the schematic of the capacitor charger shown in Figure 12, Q0 is a buck regulator IGBT switch. Output of the buck regulator provides a variable dc voltage across the storage capacitor bank C0 that can be set by a front panel pot. Q5-Rs combination discharges the voltage on C0 when the control voltage of the buck regulator is reduced. During the burst mode operation Q0 is disabled. The value of the C0 has been chosen large ~9mF so that during the 10 kHz burst mode operation, the inverter bus voltage does not fall by more than 25%.

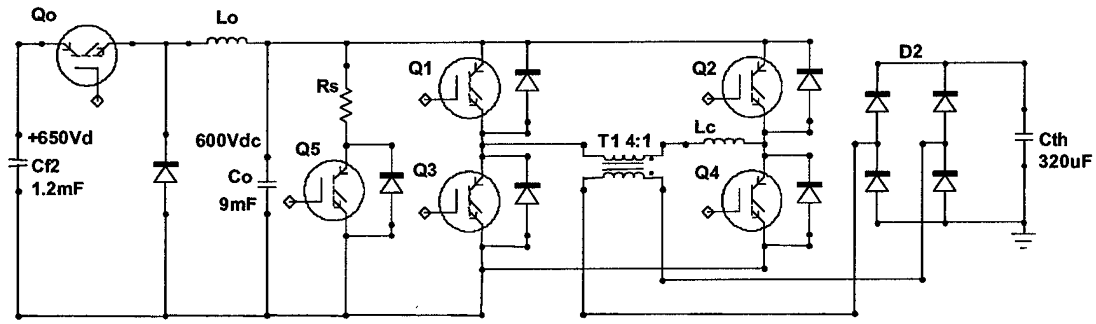

Figure 12. Schematic circuit of the capacitor charging module.

The bridge inverter applies an alternating voltage across a 4:1 step down ratio transformer T1. The thruster capacitor Cth (320 μF) is charged through output bridge rectifier D2 that rectifies the secondary winding voltage of T1. Inductance Lc is chosen to be 25μH to complete the Cth charging cycle in 80 μs. By changing the polarity of the output rectifier, Cth can be charged in negative polarity. Figure 13 shows the test voltage waveforms across the thruster capacitor that was chosen to be 50 μF for the testing purpose.

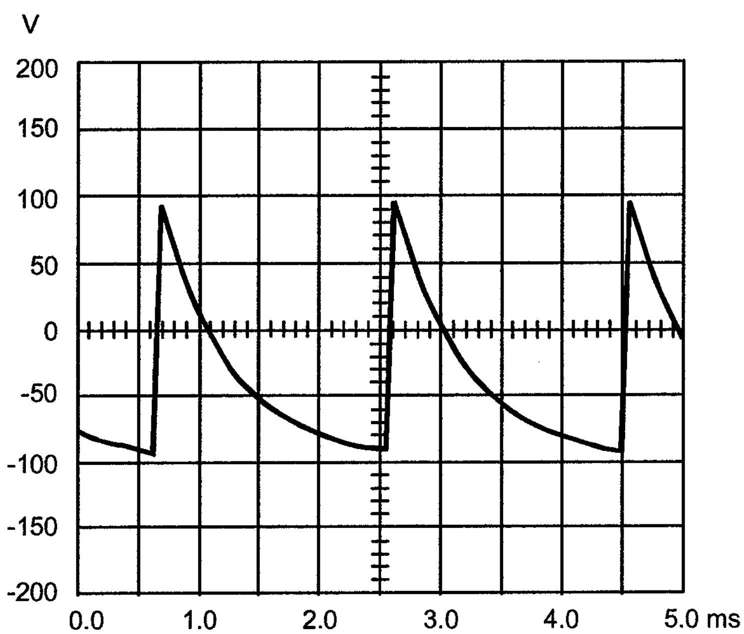

Figure 13. Thruster capacitor charging voltage waveforms at 500 Hz frequency.

4.2. GF-PPT Hardware Development

The advanced GF-PPT hardware development was described earlier in Section 3.3. We have designed the thruster hardware to operate at 10 kW average powers, and 100 kW peak power for 10 msec pulse durations. This design will enable testing the GF-PPT approach at high Isp ratings, and with conversion efficiencies approaching 25 % (wallpug).

SRL has developed advanced GF-PPT thruster hardware that offers a significant advance in electric thruster technology and performance. We have designed the GF-PPT hardware to produce 25% thruster efficiency using noble gases and/or hydrazine as the fuel. The GF-PPT hardware has not been tested in a calibrated space chamber, and consequently the ultimate performance specifications for the thruster design have not been explored. The GF-PPT hardware is now ready for thruster test and evaluation in a space chamber, which can be pursued on a follow-on program.

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[7] J.Zeimer, "Use of Water-Based GFPPTs for Future DARPA Missions", presented to DARPA, Alexandria, VA (May 2001).

[8] J. Zeimer, et.al. "Performance Characterization of a High Efficiency Gas-Fed Pulse Plasma Thruster," AIAA Paper AIAA-97-2925 presented at AIAA Joint Propulsion Conference, Seattle, Wa. (July 6-9, 1997).

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APPENDIX

Mission Analysis Summary

SRL/JPL made much progress on the mission analysis under this DARPA contract. As a result of the mission analysis we have determined that the GEPPT technology with its high fuel efficiency and low thrust can be combined with the water rocket. This combination of thrusters will meet DARPA's Orbital Express Program goals of quick, large delta-V maneuvers to reposition satellites in time of crisis and have the capability of fuel efficiency when there is adequate time to reposition these satellites. Table 1 represents a matrix of the four propulsion devices that are being research and their corresponding I_{sp}, thrust and power capabilities. From this table it is clear that the water vapor GEPPT, with high I_{sp}, is by far-and-away the most fuel efficient of the four candidates, but it does not have adequate thrust for rapid maneuvers in times of crisis. Hence using the GFPPT in conjunction with the water rocket, that has the highest thrust of the four thrusters will allow for rapid deployment of the satellites.

Comparison of Water-Based Propulsion

Propulsion Device	Isp	Thrust	Power
Water Vapor GFPPT	5000 s	1-50 mN	0.1-5 kW
Microwave Thruster	300 s*	100 mN*	1 kW
Resistojet	150 s	20 mN	200 W
Water Rocket	400 s	40-400 N	200 W*

* Microwave Thruster Performance Estimated

* Electrolyzer Power

- **GFPPTs provide the highest I_{sp} of any water-based system**
- **GFPPTs can easily be used in combination with higher T/P system**
- **The I_{sp} and thrust of a GFPPT can be throttled over a wide range**
- **GFPPTs have the smallest impulse bit, between 10-100 μNs**
- **Other benefits:**
  - Design simplicity promotes reliability
  - Excellent shot-to-shot repeatability
  - Operation at low voltage (100-400 V)
  - Quick turn-on time (no heaters, etc.)

TABLE 1

Science Research Laboratory, Inc.

DETAILED PRESENTATION OF MISSION ANALYSIS

Use of Water-Based GFPPTs for Future DARPA Missions

John K. Ziemer

Advanced Propulsion Technology Group

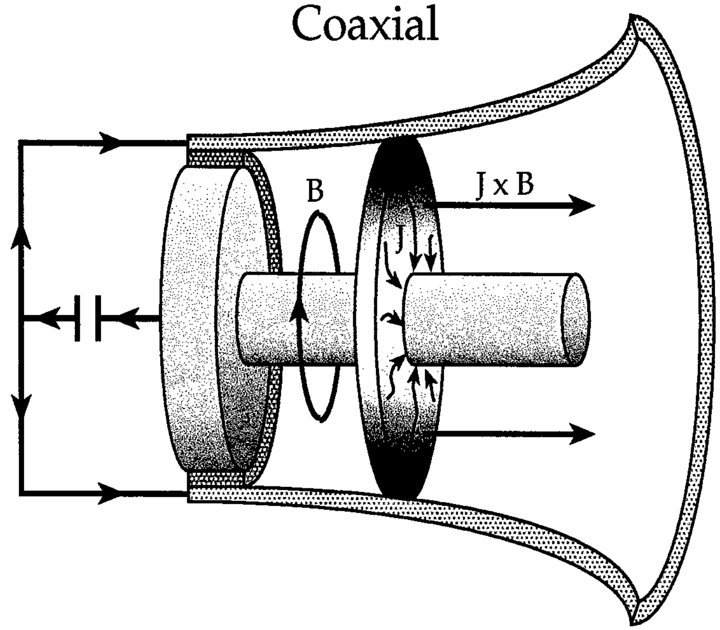
NASA Jet Propulsion Laboratory

Science Research Laboratory, Inc.

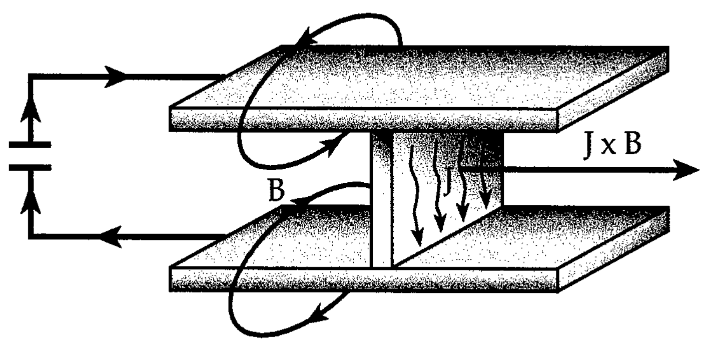
JPL

Gas-Fed Pulsed Plasma Thruster

Coaxial



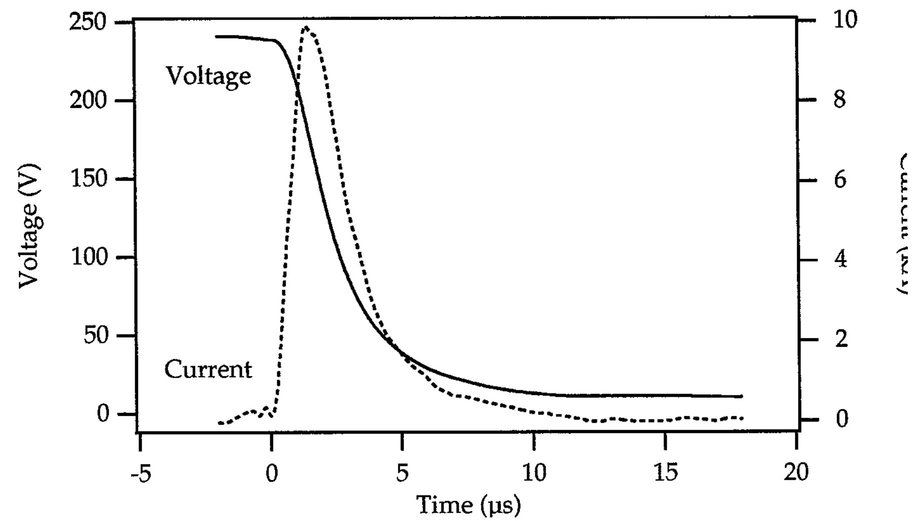
Parallel-Plate

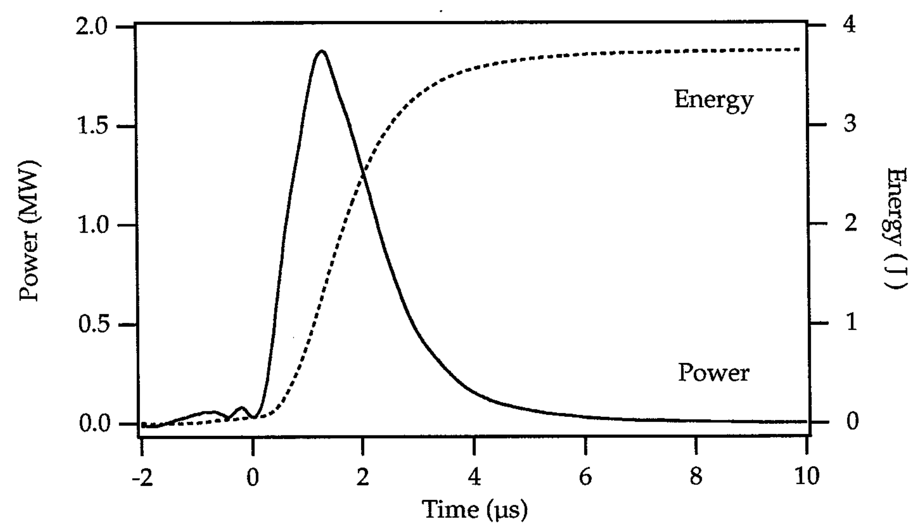


- A Gas-Fed Pulsed Plasma Thruster (GFPPT) uses an unsteady arc discharge to produce thrust
- A Lorentz force between the self-induced magnetic field and the current sheet accelerates the plasma downstream
- As the current sheet moves downstream, it entrains more propellant like a snowplow
- GFPPTs can use a variety of electrode geometries and propellant types

Advances in GFPPT Design

- Modern GFPPTs have nearly critically damped current waveforms with no reversals
- Due to the burst configuration, instantaneous power is high, but the average power and thrust can still be throttled
- Lower charging voltage allows discharge initiation to be timed more precisely
- Modern thin-film capacitors have lifetimes greater than many billions of pulses

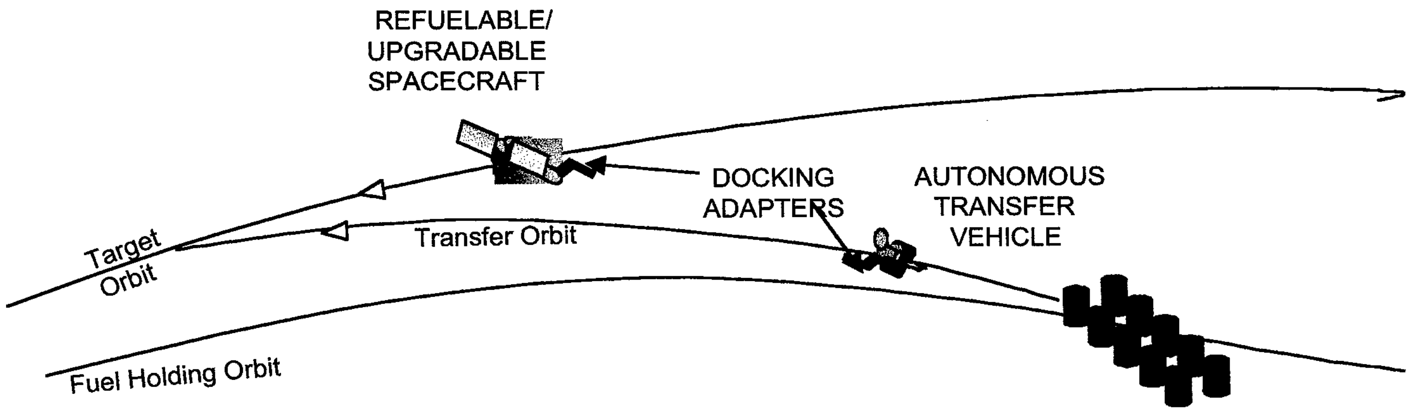




Overview of Scientific Approach

- DARPA Orbital Express Mission Requirements
  - Effects of refueling and multiple maneuvers: higher I_{sp} is better
- Results from Mission Studies
  - GFPPTs can be beneficial in combination with high-thrust Water Rocket technology
  - GFPPTs are useful for large ΔV missions where time is not a factor
  - GFPPT impulse-to-energy ratio (T/P) needs to be as high as possible
- Performance Scaling of GFPPTs
  - Performance scaling relations: obtaining higher T/P
  - Performance and lifetime measurements
- Design of Next-Generation GFPPT

DARPA Orbital Express Mission

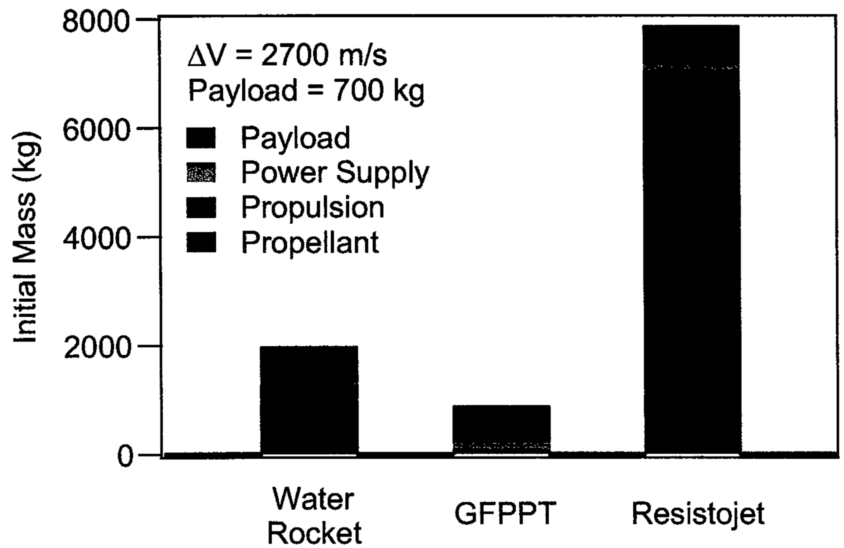


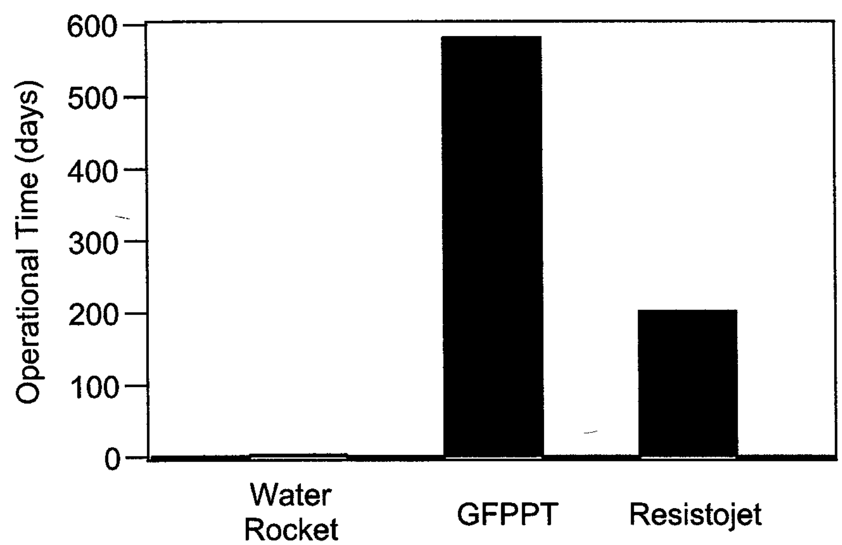
Potential GFPPT Applications:

- Primary propulsion for primary spacecraft (large ΔV, long duration)
  - Return to station, non time-critical maneuvers
  - In combination with high thrust technology like Water Rocket
- Attitude control for station keeping, fine pointing, docking, and avoidance
- Primary propulsion for orbit transfer vehicle

Graphic taken from Whelan, et al, "The DARPA Orbital Express Program: Effecting a Revolution in Space-Based Systems"

Comparison of Water-Based Propulsion Technologies





Examined two scenarios, both based on sample "water rocket" mission:

<u>Scenario #1:</u>

– Examine each propulsion technology individually

– Keep payload mass and ΔV fixed

– Evaluate propellant mass and trip time

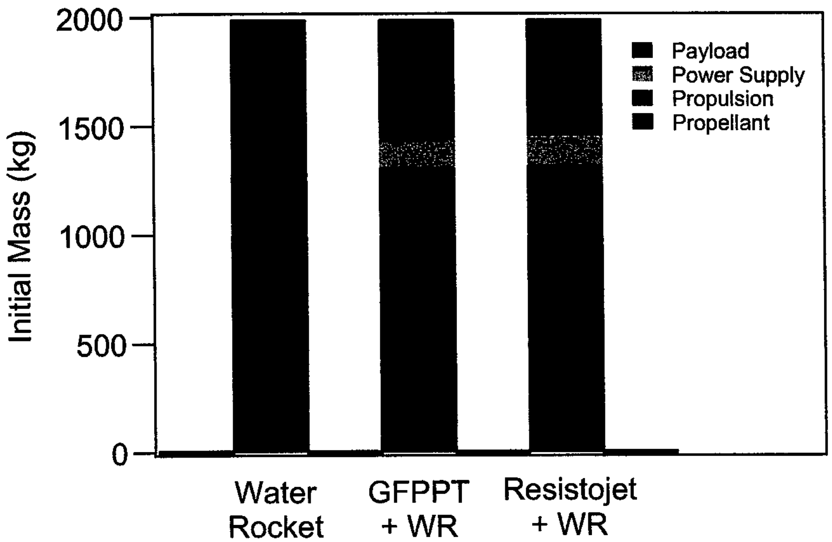
<u>Conclusions:</u>

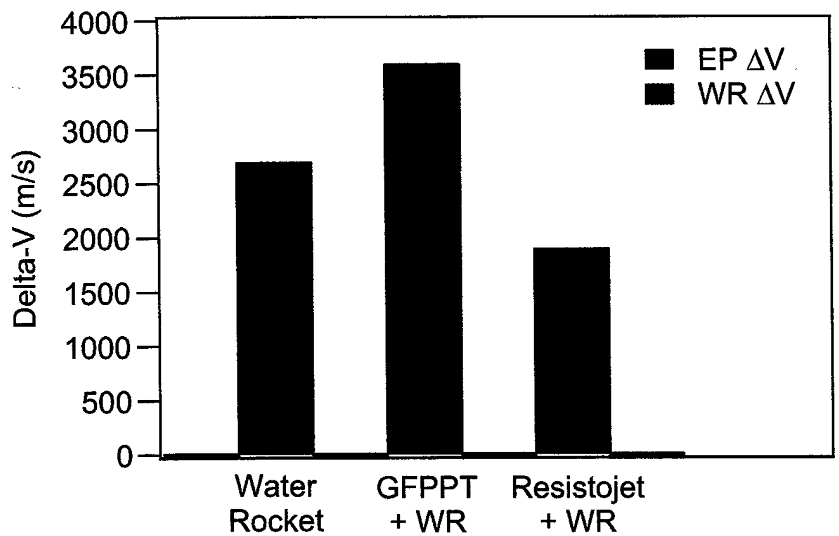
– Water Rocket offers best combination of propellant mass and trip time

– Propellant savings with GFPPT are large, however, trip time is also large

– Resistojet increases both propellant mass and trip time compared to Water Rocket

Benefits of GFPPT and Water Rocket Combination





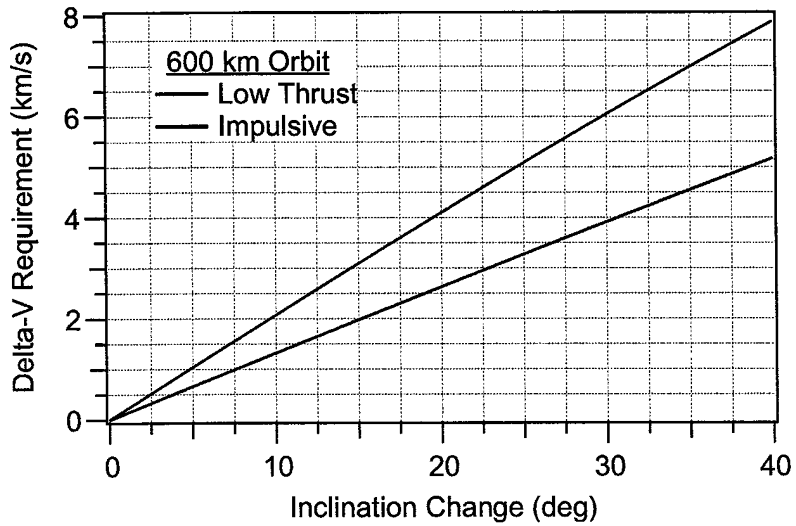
Scenario #2:

- Examine Electric Propulsion (EP) and Water Rocket (WR) combinations
- Keep initial mass (2000 kg) and propellant mass (1000 kg) fixed
- Evaluate ΔV and payload mass
- Extra power supply mass is not considered payload

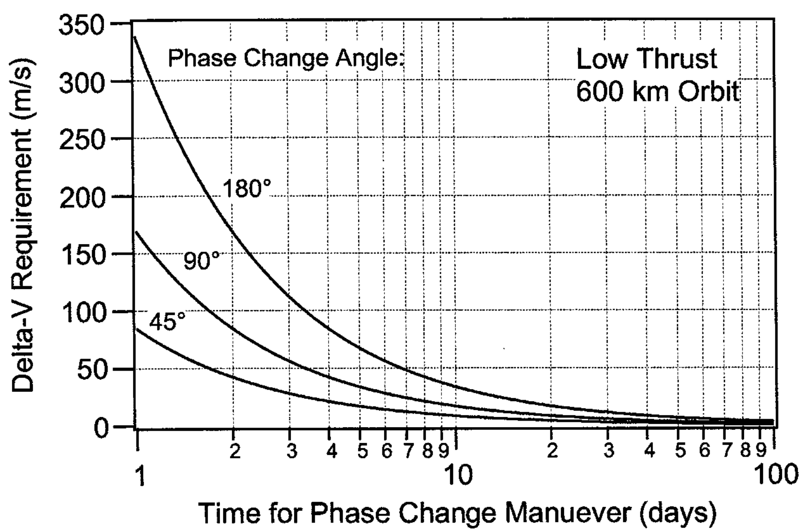
Conclusions:

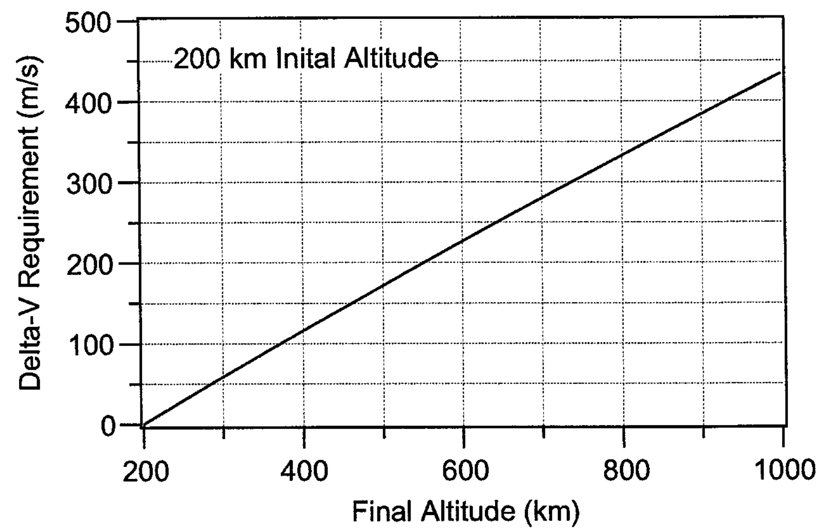
- Water Rocket and GFPPT make up the best combination for total ΔV
- For a small reduction in payload mass and high thrust ΔV the GFPPT can add a 1000 m/s low thrust maneuver

ΔV Requirements for Maneuvers

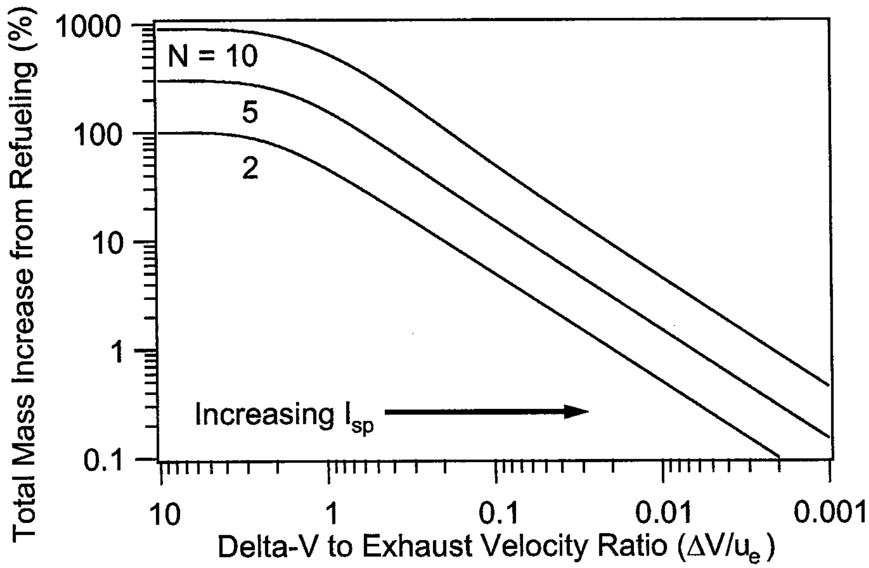


- To reposition satellites, DARPA missions will require orbit inclination and phase changes
- Transfer vehicle will need to change orbit radius and phase
- ΔV requirement can be quite large, especially for multiple maneuvers





Effects of Refueling



$$\frac{\text{Propellant Mass for N Trips}}{\text{Propellant Mass for 1 Trip}}$$

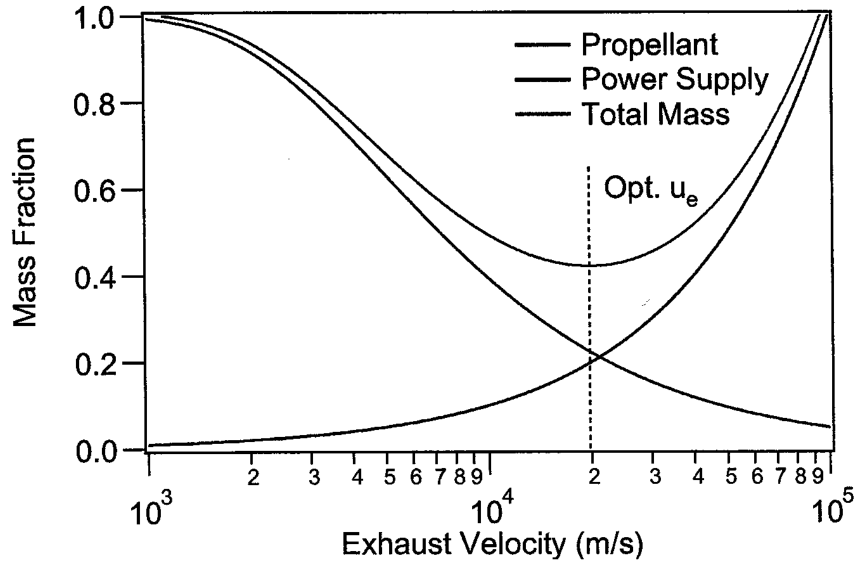
$$= \frac{N\left(1 - e^{-\Delta V/u_e}\right)}{1 - e^{-(\Delta V\, N/u_e)}}$$

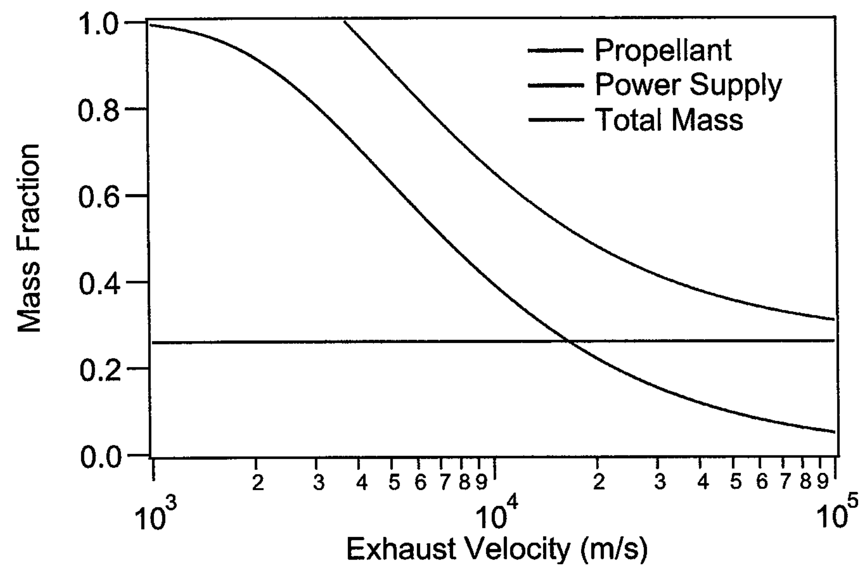
$$= 1 + \frac{\Delta V}{u_e}\frac{(N-1)}{2} \qquad \left(u_e \geq \Delta V/2\right)$$

$$= N \qquad \left(u_e \leq \Delta V/2\right)$$

- For each refueling the satellite can perform a set ΔV
- Over the life of the satellite there will be N trips and it will be refueled (N-1) times
- The total delta-v over the life of the satellite is ΔV x N
- For the same total ΔV, the total amount of mass launched into orbit increases with N
- As the exhaust velocity (I_{sp}) increases, the amount of extra mass decreases linearly above $u_e \geq \Delta V/2$

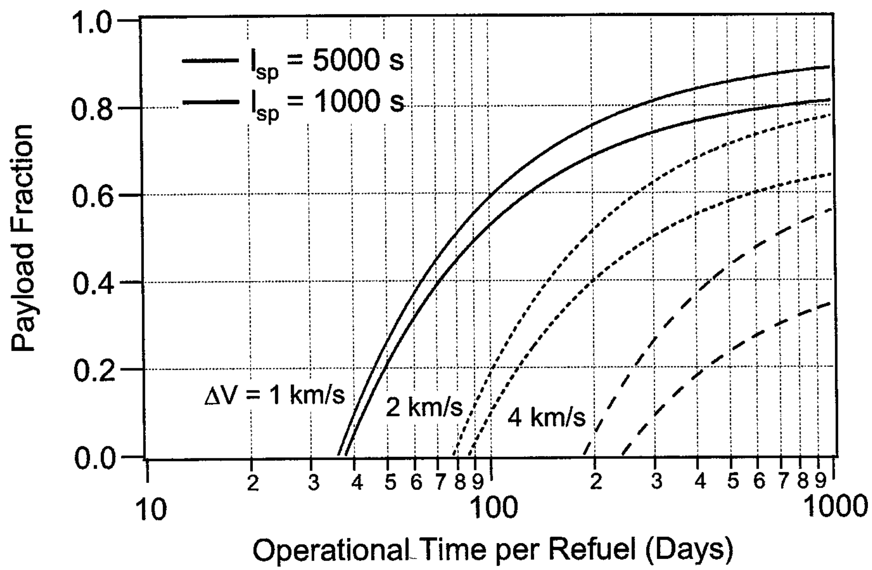
Effect of Efficiency Scaling with u_e

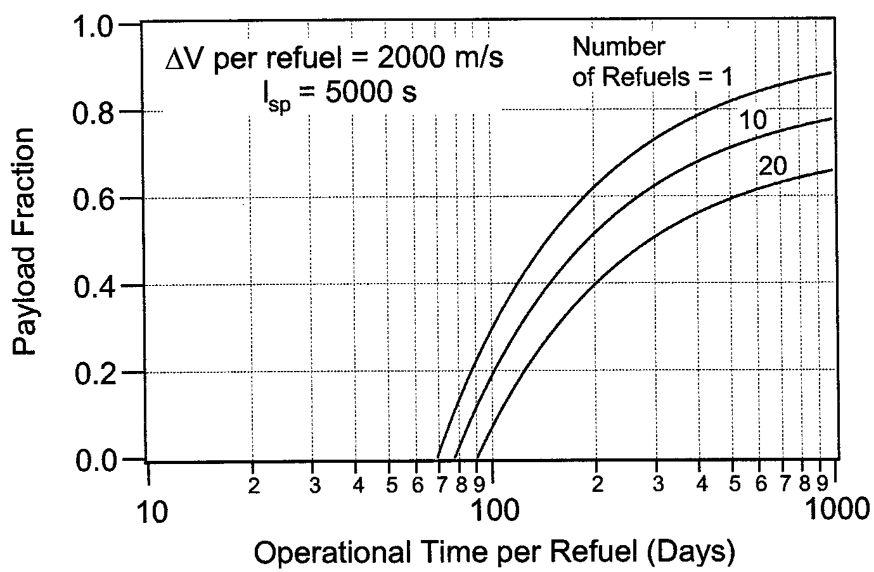




- **When efficiency does not depend on exhaust velocity there is an optimal condition for a fixed thrust level**
- **When efficiency is linearly related to exhaust velocity the mass of the power supply is constant**
  - No optimal condition
  - Mass of power supply depends on thrust (time) requirement
  - Exhaust velocity should be set to highest level possible until linear relationship with efficiency is gone

Effect of I_{sp} and N on Delivered Mass

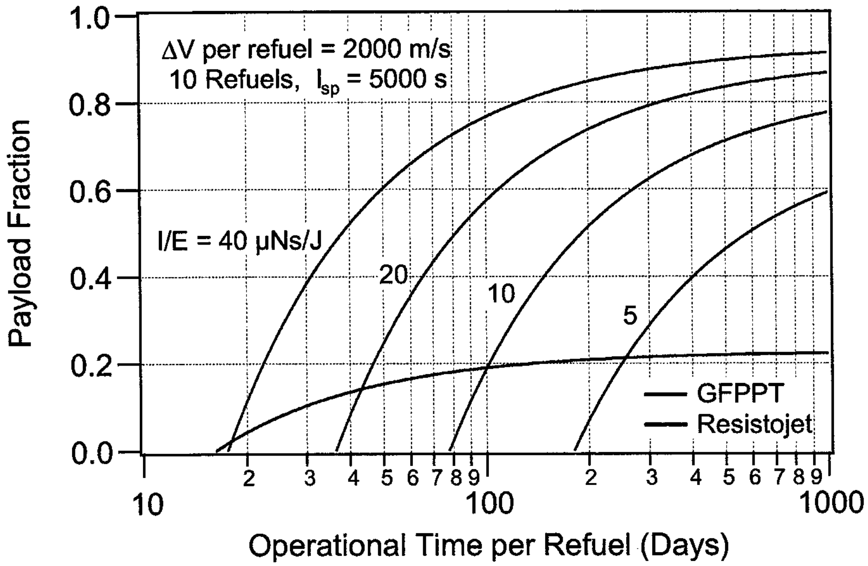


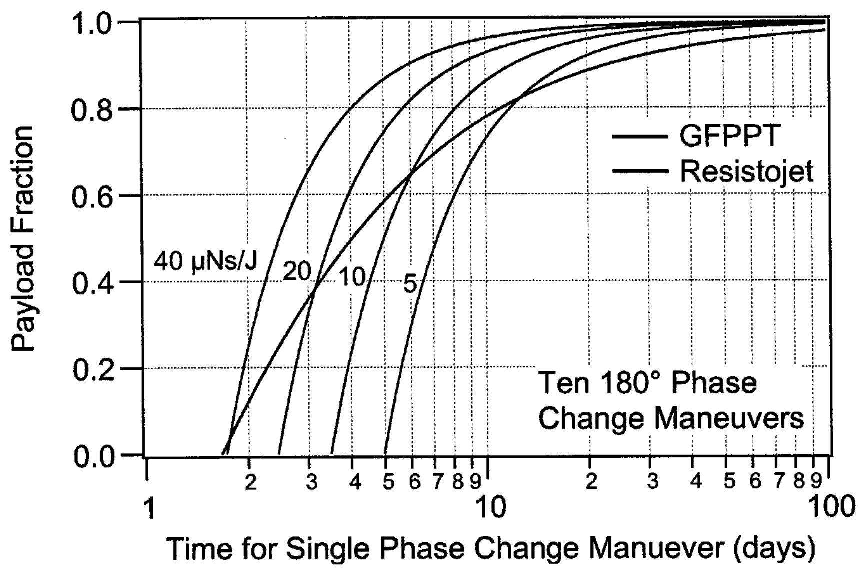


- Increasing I_{sp} reduces propellant mass significantly, especially for large ΔV
- Trip time is linearly dependant on I/E ratio and available power
- The mass of the GFPPT increases as the total impulse requirement increases
- GFPPT has a fixed lifetime, set at 1×10^{10} pulses for this study
- Lifetime is spread over total ΔV requirement for as many refuels as necessary
- Energy/pulse (mass of GFPPT) is set by:

$$E = \frac{I_{total}}{N_{ptot}} \frac{1}{I_{bit}/E}$$

Effect of I/E on Payload Mass





- **Use a baseline of 10 maneuvers per refueling with 10 refueling trips over the life of the satellite**
- **GFPPT configuration:**
  - 5000 s, variable I/E
- **Resistojet configuration:**
  - 150 s, 100 μN/W
- **Examine two missions:**
  - ΔV = 2000 m/s per refuel
  - Ten 180° phase changes per refuel
- **Choice of propulsion technology depends on time and I/E capability of GFPPT**
- **Improving GFPPT I/E ratio is critical to increasing payload and/or reducing trip time**

Performance Scaling Relations

$$I_{bit} = \frac{1}{2} L' \int J^2 dt$$

$$\frac{I_{bit}}{E} = \frac{2}{3} L' \sqrt{\frac{C}{L_0}} \; e^{-\sqrt{\psi}}$$

$$= \frac{2e^{-\sqrt{\psi}}}{U}$$

$$\eta_t = \frac{I_{bit}^2}{2m_{bit}E}$$

$$= \frac{1}{3} L' \sqrt{\frac{C}{L_0}} \; u_e \, e^{-\sqrt{\psi}}$$

$$= \frac{u_e}{U} \; e^{-\sqrt{\psi}}$$

- Relations for GFPPT performance scaling have been established
- Related to the GFPPT Characteristic Velocity

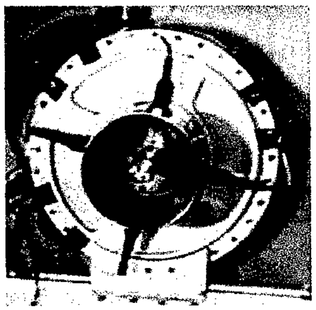
$$U \equiv \frac{3}{L'} \sqrt{\frac{L_0}{C}}$$

- Non-dimensional performance parameters:

$$(u_e)^* \equiv 3 \frac{u_e}{U}$$

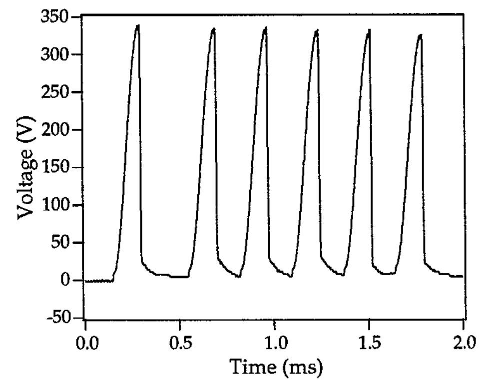
$$(I/E)^* = \frac{U}{3} \frac{I_{bit}}{E}$$

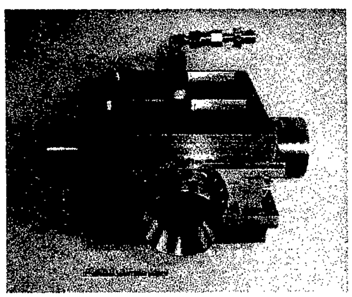
Gas-Fed Pulsed Plasma Thrusters



SRL5e-GFPPT (PT5)

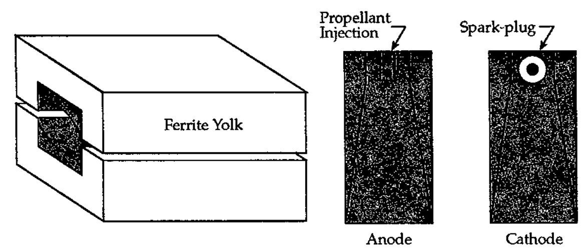
- Large coaxial electrodes
- Has a mass of ~ 10 kg with 90-270 μF of capacitance (energy between 1-8 J)
- Produces an impulse bit of about 20 μNs
- Between 2-16% Efficiency

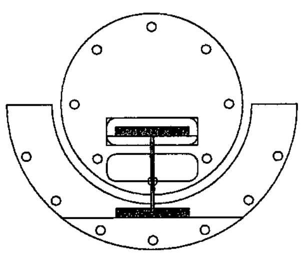




SRL6,7,8-GFPPT (Quad)

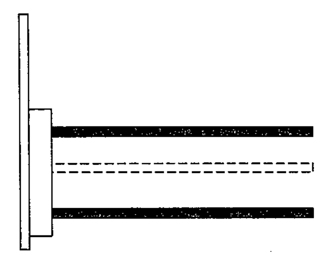
- Can use either parallel plate or co-axial electrode configurations
- Has a mass of ~ 1 kg with 64 μF of capacitance (energy between 1-2 J)
- Produces an impulse bit of about 8 μNs
- Between 2-20% Efficiency
- Has been modified to use water





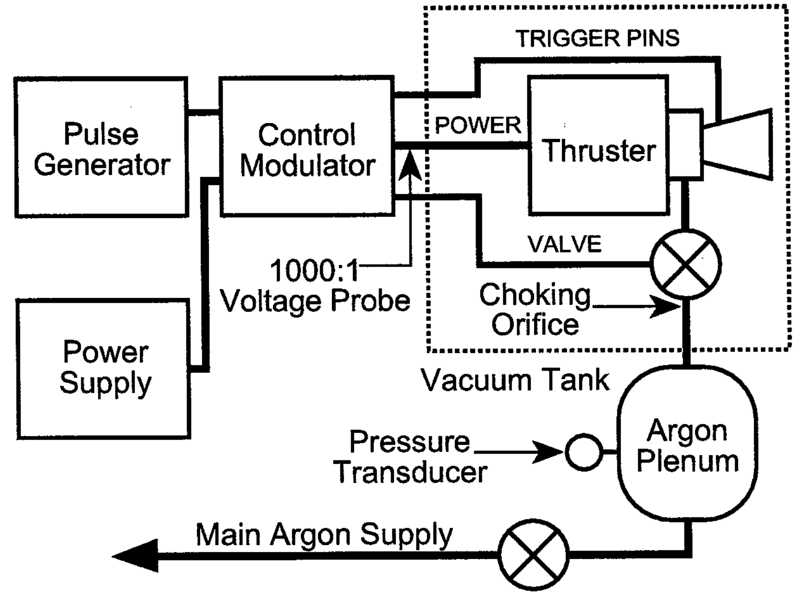
SRL9e-GFPPT (PT9)

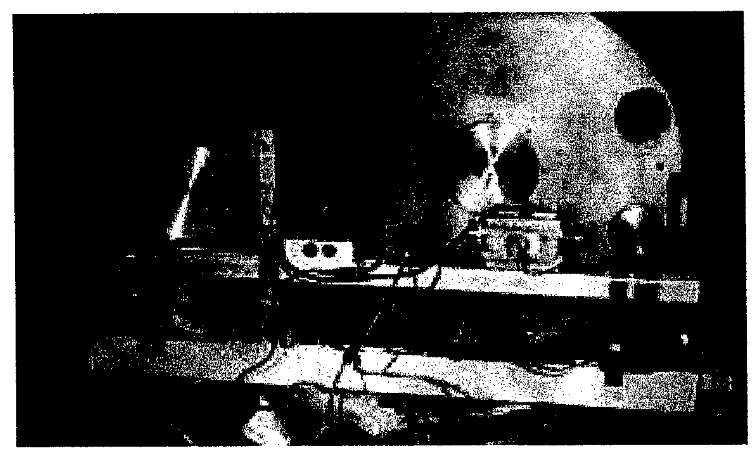
- Copper Tungsten. Parallel plate electrodes
- Uses PT5 body with modular electrodes
- Produces an impulse bit of about 20 μNs
- Between 2-25% Efficiency



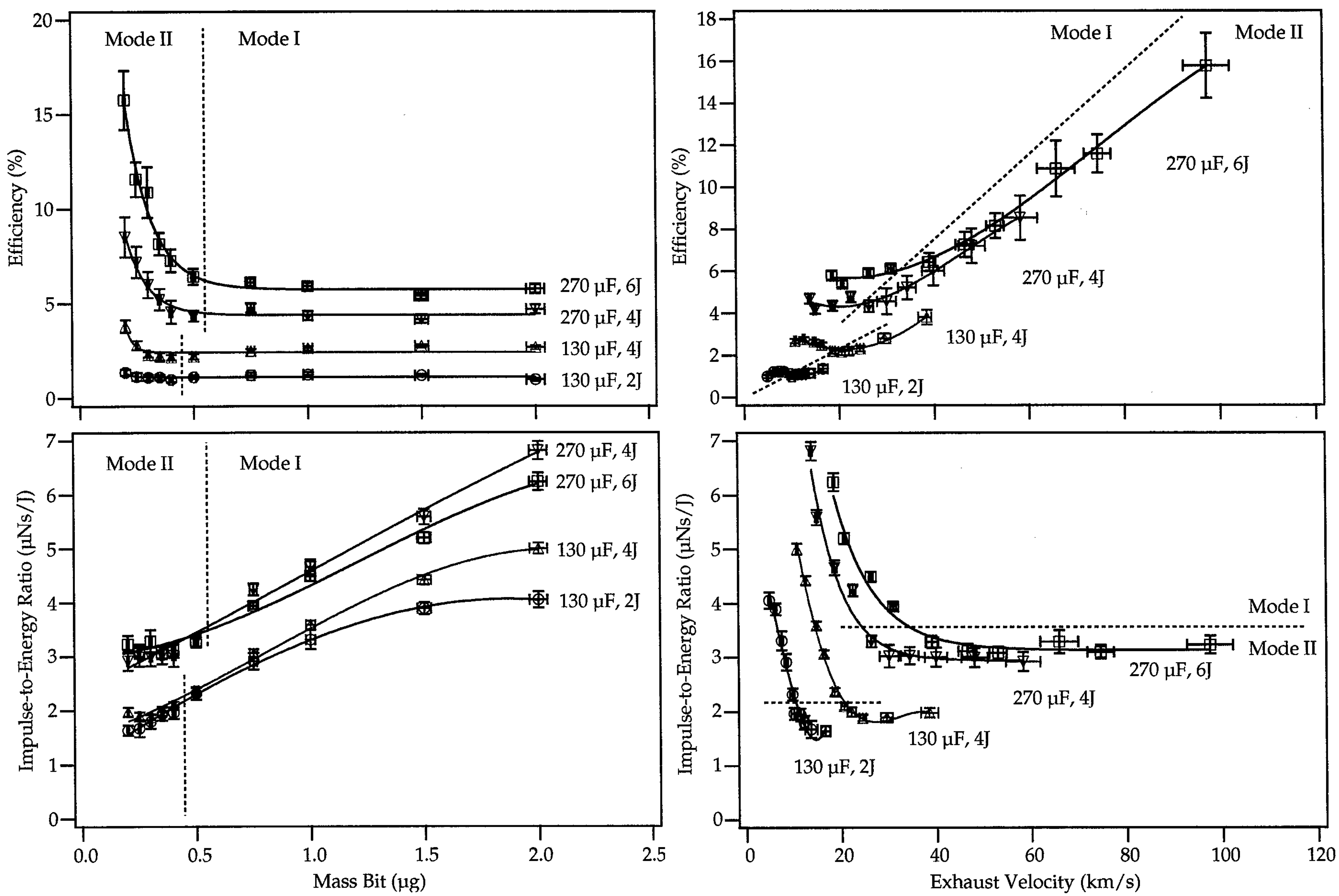
Experimental Set-up

- Position is measured with an LVDT and LabVIEW vi
- Mass flow rate is measured from the plenum pressure upstream of a calibrated sonic orifice
- The main solenoid valve is mounted on the thrust arm and opened once per burst
- Discharge current and voltage are determined from measured voltage at modulator
- Discharge initiation voltage triggers RF signal to spark-plug
- Time between pulses in a burst is variable (mass loading)

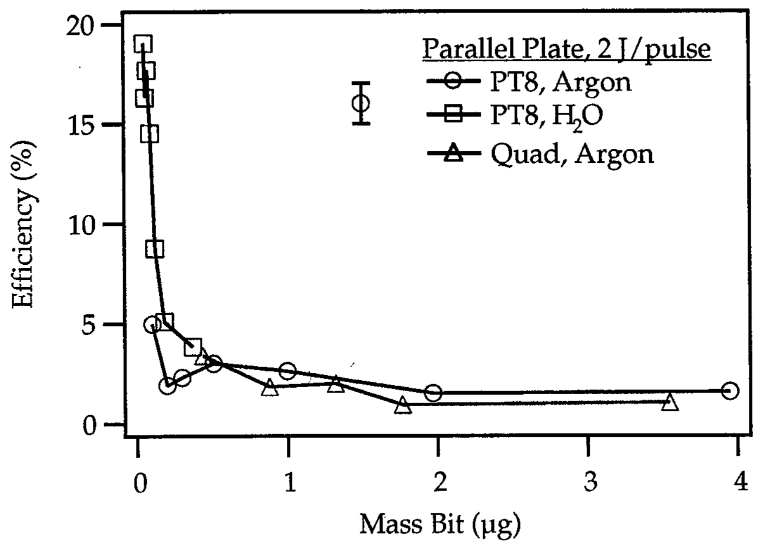


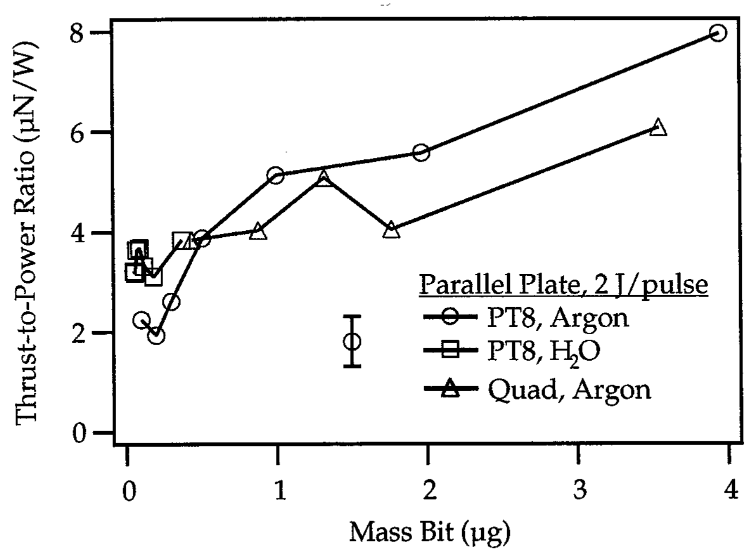


Performance of PT5



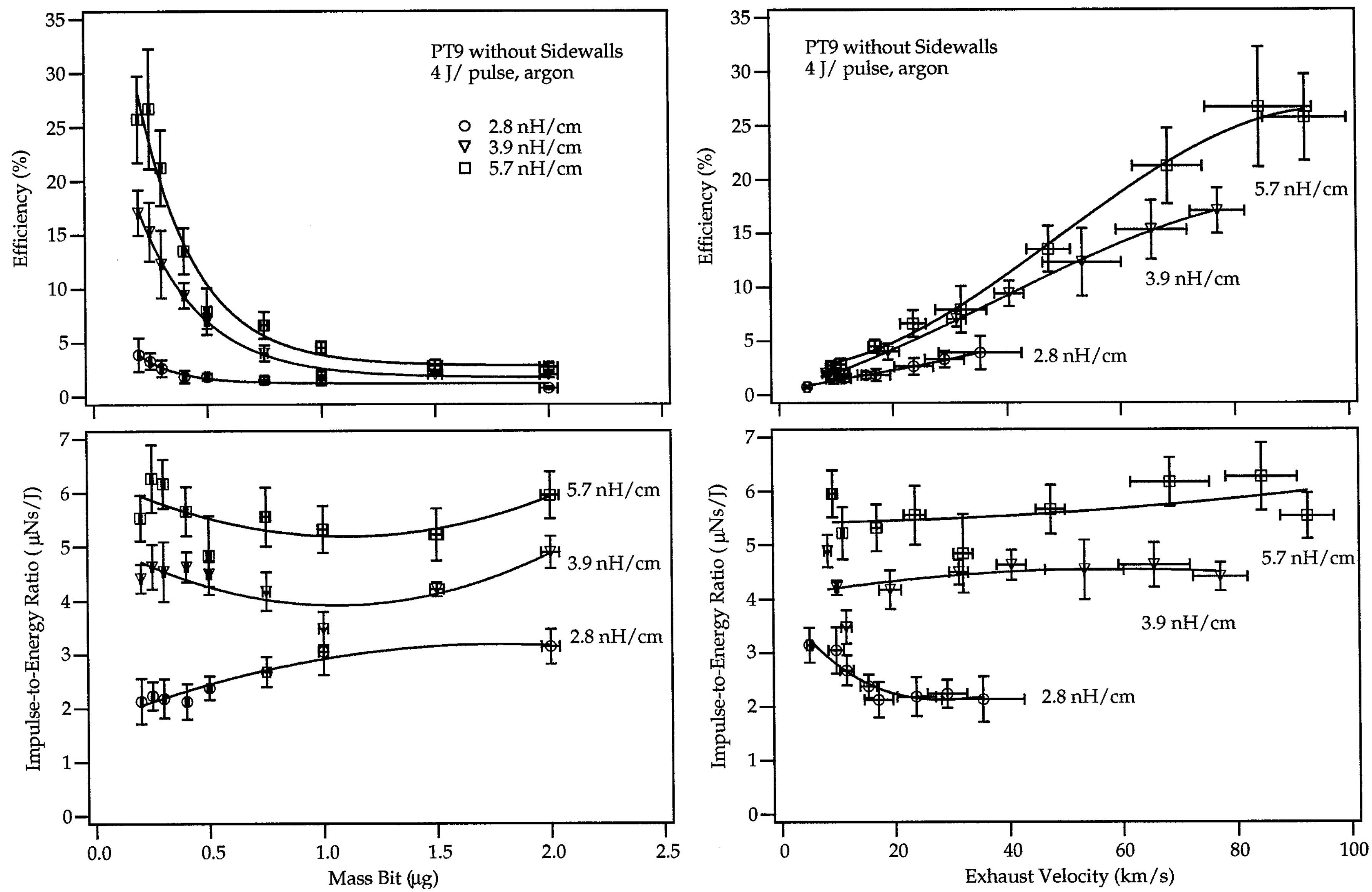
Performance Measurements PT6-8



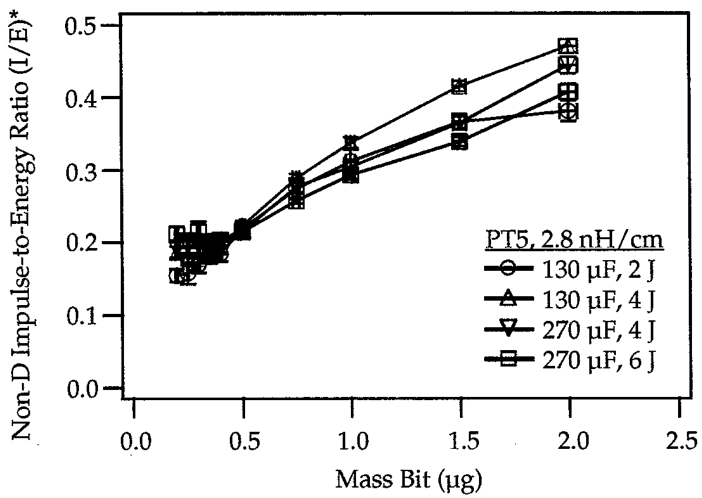


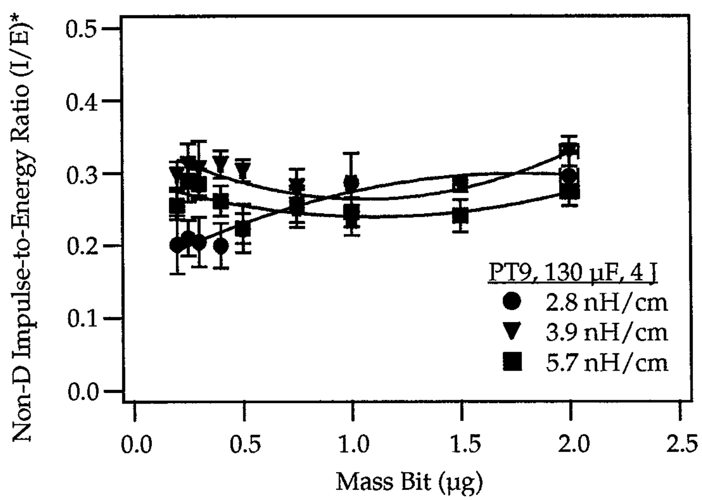
- **PT8 used both argon and water vapor for propellant**
- **PT8 performance with water follows similar trends as expected with argon**
- **Efficiency and I_{sp} increase with decreasing mass bit**
- **Thrust-to-power increases with increasing mass bit**

Performance of PT9



Impulse-to-Energy Ratio Scaling

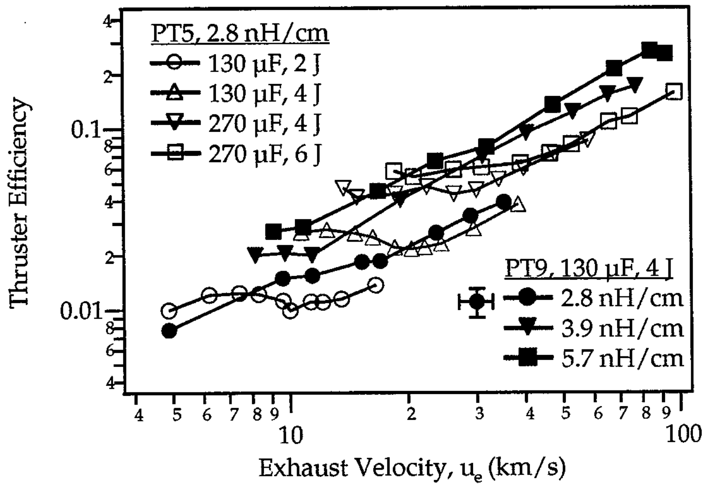


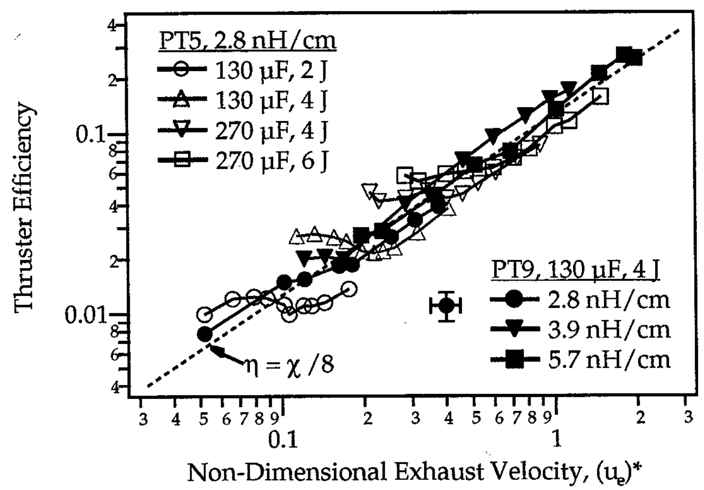


- Using the non-dimensional impulse-to-energy ratio, (I/E)*, collapses all the performance data onto very similar curves
- The value of (I/E)* is independent of the mass bit for PT9 and PT5 in Mode II operation

$$(I/E)^* = \frac{I_{bit}}{E}\frac{U}{3}$$

Efficiency Scaling with $(u_e)^*$



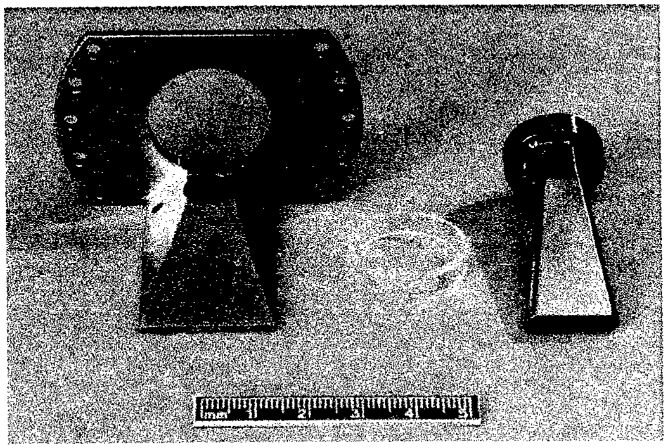


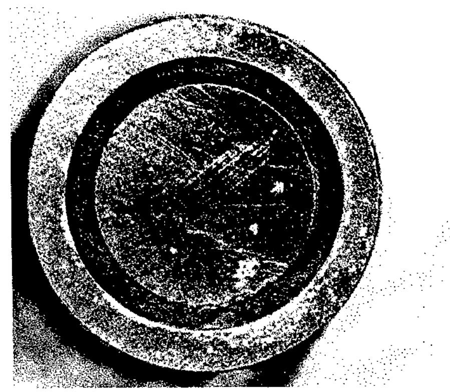
- **Using the non-dimensional exhaust velocity collapses most of the performance data from both PT5 and PT9 onto one line**
- **The largest disparity comes from Mode I operation of PT5**

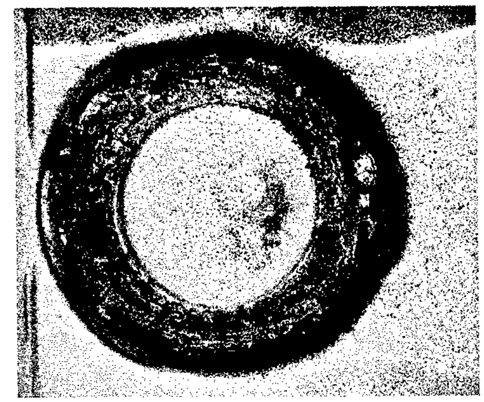
$$\eta_t \propto (u_e)^* = 3\frac{u_e}{U}$$

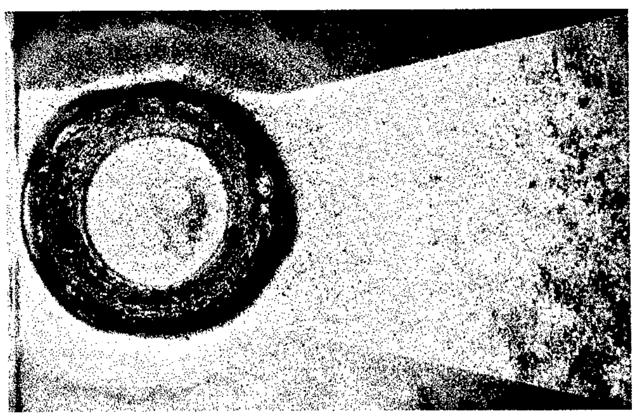
$$U = \frac{3}{L'}\sqrt{\frac{L_0}{C}}$$

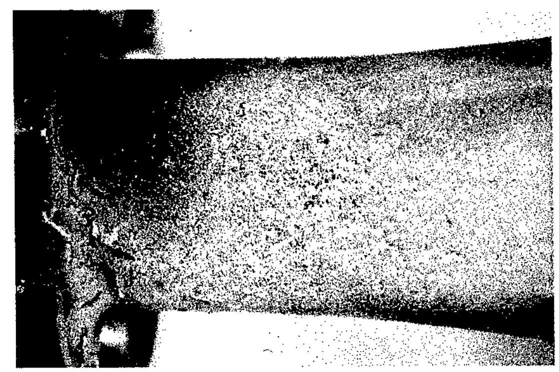
Lifetime of Quad Thruster











Pictures taken before and after 2 million pulses

Lifetime Issues

- **Lifetime is important in determining the mass of the GFPPT:**

$$M_{GFPPT} \propto E \approx \frac{M_0 \Delta V}{N_{ptot}} \frac{1}{I_{bit}/E}$$

- **Electrode erosion, especially at discharge initiation point, needs to be reduced**
  - A different source of pre-ionization could solve problem
  - Different electrode materials need to be investigated

- **Propellant management system needs long lifetime components**
  - Multiple plenum/valve combinations could increase lifetime to acceptable values

Next Generation GFPPT Design

- **Maximize inductance-per-unit-length**
  - Two different geometries will be investigated that maximize L' and minimize propellant and profile losses
- **Increase capacitance**
  - Discharge energy needs to be increased to 10 J to process total impulse requirements outlined in mission analysis
- **Increase lifetime: improvements in discharge initiation**
  - GFPPT lifetime needs to be increased to 1×10^{10} pulses to keep energy (and mass) low and total impulse high

Conservative Goal: 25% Efficiency at 5000 s I_{sp} and 10 μN/W

Optimistic Goal: 30% Efficiency at 3000 s I_{sp} and 20 μN/W